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COOPERATIVE GAME THEORY AND ITS APPLICATION TO NATURAL, ENVIRONMENTAL AND WATER RESOURCE ISSUES:

2. Application to Natural and Environmental Resources

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Abstract

This paper provides a review of various applications of cooperative game theory (CGT) to issues of natural and environmental resources. With an increase in the level of competition over environmental and natural resources, the incidents of disputes have been at the center of allocation agreements. The paper reviews the cases of common pool resources such as fisheries and forests, and cases of environmental pollution such as acid rain, flow and stock pollution. In addition to providing examples of cooperative solutions to allocation problems, the conclusion from this review suggests that cooperation over scarce environmental and natural resources is possible under a variety of physical conditions and institutional arrangements. CGT applications to international fishery disputes are especially useful in that they have been making headway in policy related agreements among states and regions of the world. Forest applications are more local in nature, but of great relevance in solving disputes among communities and various levels of governments.

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INTRODUCTION

This paper addresses the role of Cooperative Game Theory in environmental issues as is reflected through an extensive literature review.

As it is quite obvious, the possibility to solve environmental problems starts from economic elements. Economic theory generally defines two types of goods:

private goods, which verify the principle of competition: the good consumed by an agent cannot be used by another one;

public goods, which do not follow this principle: "*the use by an agent does not limit the use by other agents, there is not destruction linked to use*" (Laffont, 1985).

For these public goods, a distinction is usually made between those goods for which exclusion is possible (for example, sports clubs, water resources), and those for which it is impossible (e.g. national defence, television).

A public good is a resource from which all may benefit, regardless of whether they have helped providing the good. Public goods are also **non-rival**, that is one person's use of the good does not diminish its availability to another person (we think about the use of the television). So, public goods are characterized by the **non-excludability** property and as a result there is the temptation to enjoy the good without contributing to its creation or maintenance. This situation creates the free rider problem and, while it is individually rational to free-ride, if all do so the public good is not provided and all are worse off.

Non-excludability and non-rivalry may involve that nobody wants to pay for the provision of some services or goods, creating the, so called, public good dilemma: no one can enjoy the resource.

A Common Pool Resource (CPR) is a set of private goods (fishes, trees...), for which it is both difficult (but not impossible) to exclude from use and for which the cost of defining individual rights is prohibitive. CPRs can be distinguished according to the level of control on use: the situation is one of open access if it allows entry to anyone interested.

Here again the problem is the **non-excludability** of a common (jointly extracted) resource, but unlike public goods, a key feature of commons dilemmas is the **subtractability** of the benefits (the opposite of being non-rival): the tree I cut, the fish I catch, is not available for others.

It is becoming clear that environmental goods could be either public goods or common pool resources, with specific problems linked to these types of goods. Facing environmental issues, human beings are involved in two different kinds of economic and social problems. It is possible to define, according to Kollock (1998), two broad types of multiple-person dilemmas in terms of how the costs and benefits are arranged for each individual:

1. first type known as social fence: the individual is faced with an immediate cost that generates a benefit that is shared by all (**the provision of public goods**);

2. second type known as social trap: the individual is tempted with an immediate benefit that produces a cost shared by all (**the tragedy of the commons or the problem of appropriation**).

The potentially noxious outcomes of both types of social dilemmas stem from what economists refer to as externalities which are present "*whenever the behavior of a person affects the situation of other persons without the explicit agreement of that person or persons*" (Buchanan 1971, p.7).

Broadly speaking, externalities are uncompensated interdependencies. Therefore, the issue revolves around the study of social dilemmas which is the study of the tension between individual and collective rationality: individual rationality leads to a situation in which everyone is worse off than he might have been otherwise.

As individuals we are each better off when we make use of a public resource without making any contribution for its provision, maintenance, or regardless on its consumption, but the aggregate outcome of these individually reasonable decisions can be disastrous. The famous "tragedy of the commons" also stresses this statement (Hardin, 1998). In a social dilemma, individually reasonable behavior leads to a situation in which everyone is worse off.

As we can see in the literature on environmental economics, the market mechanism alone doesn't resolve the problem of externalities that lead to market failure because the market for environmental goods and services cannot always monetize environmental services and/or damages and quantify their economic value or attach a price or cost tag to them.

The presence of externalities constitutes a possible market failure and also leads to another problem where individual actions affect others' welfare, but there isn't any incentive for anyone to address such problem.

It seems necessary that a super-authority (typically the state) should take some kind of intervention in the market mechanism to protect those groups that are harmed. This is exactly what the state does in several cases: for example, it defines the acoustic emission limit for airplanes, because it is difficult for the airline companies to offer spontaneously aid to the people who reside close to an airport; it intervenes whenever there is an international action to be taken. It is unlikely, for example, that a spontaneous reduction of acid emissions on behalf of inhabitants of the European continent would create the acid rain destined to fall on the Scandinavian Peninsula. But also the state's authority in several cases is useless.

All these problems are at the basis of the market's mechanism failure. Market mechanisms don't consider strategic interaction among economic agents and the adjustment between demand and supply follows an automatic pattern. Including the strategic interactions among agents could bring more relevant solutions to economic problems, because it allows considering the behavioral actions of players and their consequences.

Game Theory could be used in these contexts because of its capability to address the economic and social problems of pollution, consumption of resources, and sustainable development. Game Theory studies strategic interactions among decision makers (players—persons, firms, nations, etc.), especially when the actions taken by a certain player affect others; such as is the case of pollution or, in general, of environmental externalities.

Generally speaking, human beings have the right and the duty to live on the planet together with the environment. It is quite obvious and quite well known that human beings affect, with their activities, the environmental variables, aspects, elements but also the reactions of the remaining human beings. Vrieze (1995, 1996) speaks about an "environmental game" that is played between two agents—a human being and the environment. The game shows two different levels of interactions: the first is the "Game of Exhaustion", in which humans and nature play their strategies against each other, and the second "Society's Game for the Environment", in which different human agents affect each other in terms of environmental damages.

Game Theory attempts to reach a solution for the conflicts generated between those parties, following some kind of fairness concepts for human beings and Nature, and following a search for a solution, which is socially, economically and environmentally sustainable.

Why Cooperative Game Theory? Negative and Positive Aspects

Such interactions between firms and a public authority or between different states are well analyzed by Game Theory, which links the economic aspect with the behavioral one; it is easy to understand that non-cooperation leads to a worse solution of the conflicts in terms of payoffs for the players and of quality for the environment (think about the 'Prisoner's dilemma' or the 'tragedy of the commons'); it is likely that cooperative outcomes are better than non-cooperative, but there are several problems in reaching these cooperative outcomes. It is very often difficult to have enforcement mechanisms to ensure that agreements are respected, or the cooperative solution might not be unique, thus strategic interactions, through other supporting actions (i.e. negotiation) could be considered.

There are several examples in which cooperation used at a local scale brings about a better result for humans and the environment in a sustainable scheme (see Rasmussen and Meinzen-Dick, 1995). But there are also several examples of how it is difficult to reach international cooperation to solve transboundary environmental problems when economic interests are concerned. Cooperation at the international level is possible with enforceable agreements, but very often there isn't an international power that enforces the agreement (Barrett, 1994).

Of critical importance is the fact that players are able to communicate with one another. This is one of the main causes of non-cooperation at an international level, and cooperation at a local level. Another critical aspect is the information which is at the core of trust in economics and social affairs, because it involves the ability to understand the real intents of the players in the game. A relevant phenomenon of insufficient information occurs in the presence of asymmetric information between parties.

APPLICATION TO ENVIRONMENTAL RESOURCES

In this section we analyze the various contributions of Cooperative Game Theory to issues in environmental management. The sectors analyzed will include:

1. Fisheries
2. Acid rain
3. Forests
4. Other applications

A review of game-theoretic models of fisheries

Fisheries may be classified as *destructible renewable stock resources*. Much work was done in the past to address the problem of overexploitation that affects this resource. Game Theory offers some insights into this issue and provides some interesting ideas to understand better how it could be addressed.

Knowledge of the ecosystem is needed in order to build up resource management models. Most of the game theoretic models dealing with the fisheries are studied within the framework of a biological model that can describe the population dynamics of a fish population.

The biological models underlying game-theoretic fishery frameworks can be divided into two categories: (a) models considering "few" parameters, in which the state variable is the biomass of the species population—single species-single cohort, and (b) cohort models, which are more complex. The latter case has the species population subdivided into k age classes (or cohorts) and the state variables are the biomasses of each age class. The application of one model or the other depends on the available data or on the costs to obtain data needed.

Beverton and Holt (1957) described the most commonly used model of the second type. These models take into account the age at which fish are captured; the relationship between parent stocks, average weight, and number of fish in the biomass and recruitment play an important role in determining yields. We cite also the biological model by Ricker (1954) and Schaefer (1954), a model of the first category, which is the most used. Ricker developed models in discrete time while Schaefer extended the model to consider continuous time. The reader can find a brief explanation of both types of models in Appendix I.

Kaitala and Munro (1993) and Grønbæk (2000) summarize the most important basic issues of the fisheries sector. They provide interesting ideas about the problem affecting fisheries and state that it is useful to consider several fisheries' management types that can involve different game theoretical settings:

- A shared stock: in this class are considered the fisheries that are jointly owned by two or more coastal states. Due to the presence of the Exclusive Economic Zone (EEZ)[1], managing these fisheries is often presented as a duopolistic model consisting of two countries sharing a resource and comparing the results attained in the cooperative and in the non-cooperative equilibrium. In general, extension to the *N*-person game is quite simple.
- A transboundary resource: a transboundary resource is a resource that moves, migrates or straddles across boundaries. This is characterized by species that during their life-cycle or over seasons cover several areas/boundaries often referred to as EEZ, but which also can pass through high seas. This kind of resource presents more problems than the shared stock fishery—there aren't property rights on the high seas fisheries and many agents can exploit the resource.
- Thinking about straddling fishery (like tuna) travelling from a coastal area, within an EEZ, to high seas, either coastal states or distant water fishing nations could have interest in the resource. The fact that coastal states each fish in their own EEZ for the same resource makes that situation very asymmetric (Kaitala and Munro, 1993). This problem does not arise in the case of shared stock as far as property rights are determined.
- Regulated open access (also called restricted open access) and limited open access (also called controlled access): in the first case, only activities are controlled, not fishing power or number of fishing units, but the main point is that the number of participants is restricted. In the second case the number of fishing units or fishing power is controlled. The main management instruments in regulated open access are area and seasonal closures, limitation on fishing gear and TAC (Total Allowable Catch). The limited access is either direct (number of boats, traps, horse power etc.) or indirect (Individual Transferable Quota system, ITQ).
- An open access fishery: this kind of fishery is completely out of control. It is very often destined to overexploitation. We can also say, and we will also show, that open access is often the situation occurring when there is a competitive regime governing the resource management.

Obviously, many and different problems can characterize each type of fishery; we can see that the simplest case is to have a shared resource to be managed. In this case, the property rights are defined and often some kind of cooperation can arise.

Problems have arduous answers and the huge literature, with many international conferences, about fisheries' issues confirms this statement. In addition, there are enormous economic interests in fish resources (see for example the whaling in North

[1] The EEZ was instituted in the Law of The Sea Convention signed at the end of the U.N. Third Conference on the Law of the Sea in 1992, which was declared an international treaty law. This Convention states that coastal states have full property rights to the fishery resources within the EEZ.

Atlantic and Pacific Ocean, or the tuna fish harvest), so that much work has been and will be done to address all the concerning issues.

As anyone can argue, most circumstances and applications in fisheries involve a temporal dimension. Thus, most of the analyses use a dynamic game setting[2].

We should introduce the information systems that are used in characterizing non-cooperative game theory in a dynamic game setting; this knowledge is necessary to understand researchers' cooperative results about fisheries' issue:

- Open-loop information: indicates that the player's strategy is chosen at the beginning of the game and remains the same over time;
- Closed-loop information: players have full information on the development of the game (or the evolving of the stock) and are able to change strategies during the game;
- Feedback information: agents have only information on the current stage not on the evolution of the process. This structure allows actions to be a function of the state stock.

In correspondence with these three information structures, there is a classification of Nash equilibria: open-loop, closed-loop and feedback (for feedback Nash equilibria, markovian Nash equilibrium or closed-loop no-memory Nash equilibria are used as synonymous in the literature). All of these are Nash equilibria for the games obtained when the choice of strategies is bound to one of the three classes listed above.

Cooperative bargaining approaches in fisheries' management

Cooperative bargaining: the Nash solution

The first applications of Cooperative Game Theory (hereafter CGT) to fisheries management deal with two person agents harvesting a shared fishery resource. Remembering that very often these resources cross the boundaries of at least two coastal states' EEZ, naturally conflicts can arise between involved harvesting nations. Moreover, it is clear that each nation's behavior affects the other (in general, negatively). It is also clear that some kind of cooperation should arise between harvesters.

One of the first applications of the CGT to the fisheries management issue is, to the best of our knowledge Munro (1979). He proposed a dynamic model of fisheries, combined with Nash's (1953) theory of two-person cooperative games. The population dynamics in

[2] Dynamic game-theory models are developed in both discrete and continuous time: if it is considered a discrete time, the game is said 'difference game' (or broadly 'dynamic game'), while 'repeated game' is a special case; when the time is assumed continuous, the game is said 'differential game'. [see Hanley, N., Folmer, H. (1998). "Game-theoretic modelling of environmental and resource problems: an introduction", in *Game Theory and the Environment*, Hanley, N., Folmer, H. (eds.), pp.1-29. Edward Elgar]. The setting in fisheries issues is often assumed to be differential due to the kinds of models used to simulate the biological aspects of the exploited resource.

his work are modeled using the above mentioned Schaefer model (1954). The problem formulation in Munro (1979) is the same as that in Clark (1980), with the exception that the countries here are assumed to cooperate.

The basis of these analyses is the maximization of the discounted net cash flow from the fisheries that is the present value of the resource (PV). It is clearly a bio-economic problem since it is necessary to perceive an economic return from exploiting the resource, but it's also necessary to guarantee a continuous cash flow for sustainable management of the resource. This can be described as follows:

$$PV \equiv J_i\left(x_0, E_1, E_2\right) = \int_0^{\infty} e^{-rt}\left(px(t) - c_i\right)E_i(t)\,dt,$$

subject to $\dfrac{dx}{dt} = F(x) - E_1(t)x - E_2(t)x, \qquad x(0) = x_0$

where $x(t)$ is the size of the biomass at time t, r is the (instantaneous) discount rate, p is the unit price of the fish, $c(i)$ is the unitary cost of the fishing effort for agent i, E_i is the fishing effort of agent i and $F(x)$ is the growth function of the fishery stock; here, $i = 1, 2$.

Here we want to underline that assuming constant price in the model is a strong and far from reality statement. It is indeed well known the variability of the price in the fish market. Moreover, there are several attempts to address the fisheries' management issues when the price is not constant but depends on the market. It is the case of *market externalities*. [See Sumaila (1999)]

Another parameter is important in this function: the harvest share. This parameter is important when there is more than one owner of the resource. In this case the integrals should be:

$$PV_1 \equiv J_1\left(x_0, E_1, E_2\right) = \int_0^{\infty} e^{-rt}\alpha\left[\left(px(t) - c_1\right)\right]E_1(t)\,dt,$$

$$PV_2 \equiv J_1\left(x_0, E_1, E_2\right) = \int_0^{\infty} e^{-rt}\left(1-\alpha\right)\left[\left(px(t) - c_2\right)\right]E_2(t)\,dt.$$

The harvest share plays an important role in defining the management strategies of the owners at it is very often a source of conflict, as we will see.

What is usual to question is whether there is room for cooperation. It is simple to understand that in the case where countries have identical views on the management of the resource, the strategy taken is as if there is a sole-owner of the resource and bargaining takes place over the division of the net economic return only. We will see how this can be done.

If non-cooperation predominates, Kaitala and Pohjola (1988) show that with the Nash feedback equilibrium solution, the more efficient agent eliminates the less efficient resource owner. But in this case the resource is far from its optimum because the efficient nation must harvest strongly the resource to oblige the less efficient nation to leave the fishery. It is the competitive regime that takes place in the fishery management and the resource is often overexploited. Only if pre-play communication on the harvest share between players is allowed, they jointly manage the resource, but even in this case the fate of the resource is overexploitation.

While talking about shared resource problems, the literature very often assumes that the Nash feedback equilibrium represents the competitive outcome of the management. It is clear that cooperation must take part in the management of the resource, since anyone could be better off. Obviously, in such a case the joint objective of the two harvesting agents ($i = 1, 2$) can be expressed in the following way, because every player has its own preferences over the fishery:

$$\max imize\ PV = \beta PV_1 + \left(1-\beta\right) PV_2, \quad where\ 0 \le \beta \le 1$$

where β is a bargaining parameter which permits the establishment of trade-off between the management preferences of the two countries. To determine which β is most likely to arise out, a bargaining theory is required. If $\beta = 1$, the management preferences of Country 1 are wholly dominant; if $\beta = 0$, those of Country 2 are wholly dominant. If $\beta = 1/2$, the same weight is given to the countries' management preferences. The situation here is like the countries don't have differences in management preferences. Such situation occurs also when there is one social manager that exploits the resource, because we can think that there is only one optimal management scheme according to precise preferences.

To determine which β is most likely to emerge, a bargaining theory is required. Suppose that the payoffs for the two countries are denoted by π for country 1, and θ for country 2. Nash proved that to have a unique solution for the bargaining problem, in a situation in which his well known axioms are guaranteed, we have to maximize this expression:

$$\max imize\left(\pi^* - \pi^0\right)\left(\theta^* - \theta^0\right)$$

where π^* and θ^* are the solution payoffs and $\left(\pi^0, \theta^0\right)$ is the disagreement point. This point is represented by the payoffs for the harvester in a competitive regime.

In such a solution scheme it is clear that the bargaining power of the countries depends on the relative position of the disagreement point: as one gains more from the cooperation with respect to its threat point[3], as it has less bargaining power in the negotiation. This is a point due to the kind of solution which is chosen. It can be seen that there are many other cooperative bargaining solution concepts and we will see which are applied in fisheries' management (Armstrong, 1994).

Hence, bargaining is used to solve the conflict arising when there are different preferences over the harvesters, searching also for a most suitable outcome for the resource.

Very often there are many differences between the harvesters' preferences. This is due to differences in the perceived discount factor, differences in effort costs and quite often in consumer tastes. An example is the Arcto-Norwegian cod stock. This is a stock jointly owned by Norway and Russia, which have different economic and social perspectives (see the subsection relative to the Arcto-Norwegian cod stock).

Munro (1979) presents several situations that can occur in this scheme: differences in the social discount rate, in the effort costs, and in the consumer tastes between the harvesting nations. It is also important to pay attention to the harvest share α. This is a very crucial parameter affecting the relative payoff for the harvesters and the involving conflicts between them.

Munro (1979) analyzes three cases:

- the inconsistent view on the social rate of discount: in this case, Munro assumes that the only difference between the countries involved is on the perceived social discount rate. He supposes country 1 having a discount rate (r_1) grater that country 2's rate (r_2); thus one country, the one which has the lower discount rate, has a greater incentive to invest in the resource than the other one. Munro shows that in this case, assuming that the harvest share is given, "*the nature of the trade-off is to give the high discount rate country's management preferences a relative strong weight in the present and near future but to allow the low discount rate partner's preferences to dominate the more distant future*" (page 362).

So far, Munro has supposed that the harvest share is not time dependent. Thus he analyzes the new situation in which this harvest share is time-variant (even without side-payments). What he found is that "*with no-cooperation, Country 1 could deny Country 2 access to the resource and could manage the resource as it saw fit*" (page 364).

The last situation allows side-payments. Munro points out that in this situation the establishment of an optimal management program is much simplified. The result is that "*…the optimal policy calls for the conservationist partner to buy out its less conservationist partner at the beginning of the program*" (page 364).

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[3] "Threat point" and "disagreement point" are used here interchangeably.

Nash bargaining scheme is also used to solve the sharing of the revenues from cooperation; these revenues are shared in equal parts by the players.

- unequal harvesting costs: in this case Munro shows that the differences in fishing effort costs, hence in harvesting costs, are irrelevant because these costs are insensitive to the size of the biomass, thus no bargaining will be required to determine the optimal management policy.

Even in this case he studies the situation with and without the time variant of the harvest share (both without side-payments). "*If side-payments are possible, the nature of the outcome will be straightforward and obvious. All the harvesting will be done by country 2, which in turn will pension off its high-cost partner*" (page 367).

The division of the return from the fisheries follows the same path as in the previous case.

- the consumer preferences: the main assumptions in this case are that the two countries are identical with respect to harvesting costs, and the unit cost of fishing effort in each is independent of the level of fishing effort. Furthermore, the social rates of discount of the two countries are assumed to be equal. Differences are presented over the countries' preferences in the fishery: in one country consumers view the fish as highly desirable food fish. In the other, consumers of fish and fish products see it as a perfect substitute for other 'trash' fish.

This case presents analytical difficulties: it is shown by Munro that there are non-convexity problems over the optimal control functions. Even allowing for side-payments, the main conclusion of Munro is that there exist multiple equilibria.

Thus, if transfer payments are allowed it is showed that there aren't problems in solving the conflict: in general, the most efficient nation or the nation that shows greater interest for the resource acts as a sole-owner, buying out the less efficient country at the beginning of the game, compensating the less conservationist with transfer payments. The management of the fishery is left only to the social manager.

Thus, the most important assumptions are on transfer payments, but also on the harvest share. In fact, if transfer payments are not allowed, the bargaining takes part not only in dividing the outcome of the cooperation, but also in order to chose the optimal harvesting program. It is important that countries accept a program in which the harvest shares vary over time. In Munro (1990) the effects of the chosen harvest share, time-dependent or independent, are shown most clearly: the better result is attained allowing time varying harvesting share and transfer payments. In this situation, the most efficient country buys out the less efficient one and manages the resource as a sole owner. But, obviously, it must compensate the less efficient country to maintain the leadership in the fishery.

As usual, side payments produce linearly distributed profits for the agreement as a whole, strictly over and above the concave Pareto-frontier for competing harvests (Kaitala and Munro, 1993).

Following Bjǿrndal, Kaitala, Lindroos and Munro (2000), let $w\left[x(0)\right]$ denote the present value of the net economic returns from the fishery, when the management preferences of the most efficient country prevail. The cooperative surplus is the value

$w\left[x(0)\right]$ minus the sum of threat payoffs. According to the Nash bargaining scheme, this surplus should be split equally between the two states.

It is important to mention that this approach assumes that agreements are binding. This is a very strong assumption, because often it is not true that this kind of contract can be made or can be maintained without having a complete trust between the parties or an external power exists that controls respective behaviors enforcing the agreement by some effective punishment mechanism.

The case of non-binding agreements

A binding agreement means that harvesters should involve themselves in an enduring commitment through an infinite time horizon.

This argument has been disputed by many authors. Vislie (1987) denies the assumption that countries make binding agreements. He proposes a different idea to construct an agreement in a way that none of the involved countries have any incentive to break the agreement during the time path. In particular, he poses the problem that fish stocks vary during the time path, and typically become lower or different from the initial stock. Agents could face different situations during the time path and assuming binding agreement doesn't allow the possibility to change the strategies taken at the beginning of the game, where it is clear that the situations are different.

The property proposed by Vislie shows a way to address this hard issue introducing the *sub game consistency* in the Nash bargaining process. In such a case a two-period model is presented. The sub-game consistency takes into account this fact and specifies the harvesting share for each country as a function of the remaining stock of the resource. The result is that a time or sub-game consistent long-term contract for harvesting a common pool of a renewable resource, determined as a Nash bargaining solution, will stipulate equal harvest shares in the last period, and a harvest share less than ½ in period 1 for the low-discount-rate country, when the status quo outcomes are put equal to zero.

Two assumptions are made: the unit cost functions are identical and the stock at the end of the second period will be equal to the critical value (there is no commercial sense to exploit the stock below this value). Vislie states that in a certain second period, in which the stock is different from the beginning but not equal to the critical value, the quantity fished is divided equally between the two countries. This is different form Munro (1979) conclusion. Here there isn't a situation in which one of the countries is excluded from the harvest. What is indeed the process is explained in the proposition.

Vislie asserts that this statement if put into the objective functional equation of the two countries, determines that the Munro's assumption on the existence of binding agreements is dynamically inconsistent. In the new proposed model there is a self-enforcing agreement without side-payments and binding agreement.

Kaitala and Pohjola (1988) offer another path to avoid the binding agreements assumption. Munro (1990) asserts, citing what Kaitala (1985) points out, that non-binding agreements are 'equilibrium' agreements and have the quality of being 'sustainable'. A sustainable agreement is one that does not call for periodic renegotiation. An equilibrium agreement is one in which neither player has an incentive to cheat. An equilibrium agreement is also sustainable.

Thus, they assume non-binding agreements. They allow for the presence of transfer payments, but these are not made once and for all at the beginning of the game (to guarantee this method, it is necessary to have binding agreements), but are continuously transferred from one country to the other. That is, a static bargaining approach is not useful.

Starting from the situation described by Munro (1979) in the presence of transfer payments, i.e. in a situation in which the optimal harvesting program is defined by the sole owner's behavior, the stock of the fishery reaches the corresponding level at which the sole owner will reach his long term optimum following an optimal dynamic path.

If we use $x(t)$ to denote the level of biomass at time t, let us state that the fishery's biomass at time 0, before the harvest has started, is $x(0)$. In the sole-owned fishery the harvester reaches the optimal bionomic[4] equilibrium using an effort equal to the relative natural fishery's growth (see Appendix I for further details):

$$E^* = F(x^*) / x^* \text{, with } x(t) = x^* .$$

If the value of the biomass stock x^* is not reached, the harvester doesn't harvest; if it is above this value, the harvest is at the maximum level.

This occurs also when there are two harvesters, but one cares for the resource more then the other or one is more efficient than the other. If transfer payments are allowed, it is shown as mentioned before that the most efficient harvests as a sole-owner and reaches his optimum now called x_1^*, compensating the second harvester with adequate payments.

However,if the transaction from the sole-owner to the less efficient occurs once and for all at the beginning of the harvest, there could be a moment after the transaction in which the less efficient harvester is stimulated to harvest: it has just received the great payment and it could be also profitable for that harvester to harvest because the stock size might be under his bionomic equilibrium (see Appendix I for further details). Only if the agreement is binding this evolution can be avoided.

Kaitala and Pohjola (1988) propose a different payment mechanism. They propose that the transfer is not made once and for all, but that there exist a continuous quotas transfer

[4] Bionomic equilibrium is said to occur at the intersection of the revenue-effort curve and the cost curve. In an unregulated fishery, this will be the natural equilibrium point, since the economic forces and the forces of biological productivity will be in balance.

as the size of the stock goes from the initial point $x(0)$ to the optimal point $x(t)=x_1^*$. They assume that the transfer payment flow from the sole owner to the other country is zero during the dynamic path of recruitment of the stock (this occurs if at the beginning if the game $x(0)<x_1^*$), and that it is a constant in all the other cases (when the stock size is equal or grater than the optimum): the transfer payment has to be feasible at each stock level that will be reached during the agreement.

With this shift from binding to non-binding agreements, Munro (1990) asserts that there is a lower chance for cooperation between the agents and that this method requires additional insight, as will be seen later.

To sustain this new method, additional insights are required. Kaitala and Pohjola (1988) speak in terms of *memory strategies*. The authors assume that the agents are able to use these strategies. This method is used to avoid the limit of the binding agreement approach and to propose a new method to guarantee an efficient equilibrium for the transfer payments. "*The efficient memory equilibria are as follows:*

- *The harvesting countries communicate with each other and agree on a cooperative management and agree on a cooperative management program. The cooperative management must be agreeable…;*
- *The countries agree on some threat strategies to be applied, if cooperation fails;*
- *The countries start by applying the agreed cooperative harvesting policies;*
- *If the agreement is observed, then cooperation is continued during the next period;*
- *If violations against the agreement are observed, then the countries apply their threat strategies*" (page 111).

Of course, there are additional assumptions about the ability of the countries to monitor their respective behavior. To make such an agreement, each country should allow the monitoring and should guarantee a free access to its fishery statistics; furthermore, this monitoring involves additional costs for the countries. This is an important point that must be considered when an optimal strategy is considered for adoption.

It is important to note that the proposed approach is 'differential', not 'repeated': "the game is unique at each time moment, and hence non-repeated, since the system evolves continuously according to the state equation" (page 111).

So, we see an evolution from the first Munro's assumption (1979) on the binding approach. Vislie (1987) proposed a two-time game and the sub-game consistency property to overcome the constraint of binding agreements. Renegotiation in his work is not however avoided. In this new time-setting, we can see a totally different formulation, which makes use of the memory strategies.

Kaitala and Pojola use the trigger strategies. They first introduce the ∂-strategies (∂ is a fraction of a time unit); these are introduced in a discrete time-setting. With this decision rule, the cooperation will continue, unless either of the agents wants to deviate from it for some reason. One problem is that these strategies can fail. This may occur in case the time interval ∂ and the discount rate are large. Therefore, they introduce a new kind of strategies, the trigger strategies, defined as an infinite sequence of ∂-strategies, where ∂ tends to zero. In this case, cheating or any other deviation from the agreement can be detected without delay. The authors point out that the equilibrium of the harvesting policies is not unique. But if the countries are allowed to communicate, a Pareto efficient solution will be found and there is no reason for the agents to deviate and to play their non-cooperative Nash solution.

The same threat strategies were used also in the whaling management problem by (Hamalainen et al. 1984), who developed a two-person model harvesting a stock of whales. They introduced the Kalai-Smorodinsky (1975) solution and the cooperative bargaining approach to solve the problem of overexploitation of the resource, arising when the management is out of control. It is showed by the authors that an appropriate system of threat could prevent agents from cheating and allows the cooperative solution to be an equilibrium in an infinite time horizon.

The evolution of the memory strategies and of the threats to eliminate the cheating in non-binding agreement, like here, is showed in Kaitala (1987). Also Munro (1991) offers a good explanation of the evolution of the ideas mentioned above that are analyzed in the context of differential games.

So far, we have not taken into account how it can be managed for a straddling stock fishery. All the models in this first approach are referred to a shared resource jointly owned by two countries. We know that most of the problems in fishery's management arise when we are facing a high seas fishery that is straddled between an EEZ and the neighboring high seas. It is reasonable that anyone who has interests in the fishery, should be assured a substantial right to utilize it. There are no exclusive property rights in the high seas and the problem of the new entrants is at the centre of the discussion, since the U.N. Conference in 1982 did not deal with this issue. Hence, how could these complicated fisheries be managed?

Kaitala and Munro (1993) explain that there were at least two schools of thought with respect to what is the better management program to apply for straddling fisheries: the '*consistency principle*' and the '*creeping jurisdictionalism*'. The first is based on the assumption that it is possible and useful, even for the resource, to enlarge the policy adopted in the EEZ to the neighboring high seas fisheries. The second is based on the assumption that anyone who is interested in the resource must take part in the decision assessment. Obviously, international interests give the meaning on what is the better choice to take and the international powers decide which would be the better management program for that fishery. In fact, while the first principle gives much power to coastal States, the second gives much power in the management program to the Distant Water Fishing Nations (DWFNs) and asks for cooperation to arise.

However, in their paper Kaitala and Munro offer a first answer to the management problem of the straddling stock fisheries. They reintroduce what Munro (1979) establishes in its two-agent model, but assuming that the countries involved were one coastal State and one distant water fishing Nation. The DWFN and the coastal state disagree over management strategy (differences in the preferences), but agree to avoid the open access competitive exploitation of the fishery.

If transfer payments are allowed and $\beta = 1$, having a situation in which the relevant preferences are those of the coastal State, it is likely to realize the above mentioned consistency principle: both the coastal and the DWFN can be better off. We should remember that this is true only if it is possible to have binding agreements.

Kaitala and Pohjola (1988) offer a new method to overcome this constraint and Kaitala and Munro (1993) assert that the management program proposed for the shared resources can be applied, with the memory strategies, also to the case of straddling stocks.

So far it is important to report that another problem could arise when the agreement is non-binding: the relative bargaining power can change between the harvesters because the stock changes its size during the time and this involves changes also in the threat point of the harvesters. Also, in the cooperative game setting with binding agreement these processes are linked, but in this case what is important is the initial situation only.

Within this situation, we cannot forget the new entrant problem. At the moment that we are describing, this problem is not still taken into account by the literature. Even Kaitala and Munro (1993) state that "*…it is much to be hoped that 'new' entrant' problem will be high on the agenda of the forthcoming U.N. conference*" (referred to the U.N. Conference started in 1993 and finished in 1995). We will consider later in this survey the literature dealing with this issue.

Other cooperative bargaining approaches: the Kalai-Smorodinsky and the Salukvadze solutions

We first remind the objective function that must be maximized to obtain the optimum for the harvesters jointly managing a shared resource. The function is:

$$\max imize\ PV = \beta PV_1 + \left(1-\beta\right) PV_2, \quad where\ 0 \le \beta \le 1$$

where β is the bargaining parameter allocating the right value of the harvesters' preferences.

By varying β, it is possible to obtain a Pareto frontier delimiting the feasible set in the bargaining problem. It is assumed that this frontier is continuous and concave. There are several methods to determine one specific parameter β using an axiomatic bargaining solution such as the Nash Bargaining Solution. Now we want to report some other examples of bargaining solutions often mentioned in literature:

- The Kalai-Smorodinsky solution;
- The Salukvadze solution.

While the first is well known, the second remains less studied and applied, but Armstrong (1994) offers a good insight in the application of such schemes in a real case study: the Arcto-Norwegian cod stock. The main framework in which the author wants to face this issue is the cooperative bargaining proposed by Armstrong and Flaaten (1991) and Munro (1979) where the threat point is described by an open access fishery. The reason for such study is to understand which are the main criteria allowing the managers to choose one bargaining solution over the other. There are, in fact, several studies in which Nash solution is applied, but also there are several studies in which the Kalai-Smorodinsky solution is applied (Hamalainen et al. 1984) in solving real cases.

Armstrong focused his attention on two of the three parameters affecting the bargaining outcome: harvesters' preferences and bargaining powers. We know from the above mentioned analysis that these are the most important in determining the bargaining result.

In the next section we will analyze the implication in a real case study. Now we report some conclusions at which Armstrong arrives in his paper (Armstrong, 1994):

- The Nash solution takes into account the disagreement point directly, while the maximum potential outcome only indirectly affects the final outcome through the shape of the cooperative frontier;
- The Salukvadze solution takes into account the maximum bargaining outcomes directly and the threat point indirectly through limiting of the bargaining area;
- The Kalai-Smorodinsky solution heeds both the factors—preferences and bargaining powers.

These solution concepts are analyzed when transfer payments are allowed, when they are not allowed when are not allowed are graphically confronted.

A real case: the Arcto-Norwegian cod stock and the cooperative bargaining

The Arcto-Norwegian cod stock is a particular fishery which is shared between Norway and the USSR. Spawning takes place in the Norway EEZ, while adults live in the Soviet EEZ. In 1970s there was a cooperative management arrangement between these two countries. After 1990s the situation rises in complexity because the fishery became also a high sea fishery, attracting DWFNs in the area, specifically Iceland. The conflict is now settled through a tri-lateral agreement following the UN Fish Stock Agreement (1995).

Armstrong and Flaaten (1991) analyze the possibility of cooperation between Norway and USSR through the Nash bargaining scheme introduced by Munro (1979). The model is practically the same: they assume that the demand is infinitely elastic, but they consider different harvest function for the involved nations, introducing a different catchability coefficient q in the harvest function (see Appendix I). They also assume that no side-payments are allowed. Thus, optimality is achieved maximizing the Nash product over the Pareto frontier (assumed to be concave).

Conflicts arise due to differences in the social rate of discount, in costs fishing efforts and in market prices. It is assumed in fact that Norway and the USSR face different markets, thus different prices. All three conditions were studied by the authors. The conclusion, using this method, is that the gains for the parties (Norway and the USSR), from a joint management of the stock, are very large with respect to the non-cooperative case.

Even if the population dynamic and structure are very important, this paper does not consider these aspects, assuming that the fishery is characterized by only one cohort, thus only one biomass function. This is a limit for this model because it is well known that different cohort have different habitat, i.e. live in different EEZ. Moreover, fishing juvenile results in different consequences for the stock than fishing adults.

Sumaila (1996) introduces the same game theoretic solution, using the Nash bargaining approach, but assuming that the population dynamic follows a cohort model. The author considers that there are different fishing methods, trawl and coastal vessels, and that each nation favors one of them. Each gear has different fish target and could fish in different habitat of the cod stock. The paper finds what the overall annual harvest for cod will be, and what proportion of this will be taken by the coastal and the trawl fleets; moreover, it confronts the non-cooperative and the cooperative bargaining models.

Recalling Armstrong (1994), it is important to report the schematization of the procedure he proposes to reach cooperation:

1. countries calculate their present value and their disagreement point;
2. countries together decide which kind of bargaining solution should be used;
3. the compensating value is calculated;
4. countries decide which method of compensating solution must be made.

All these statements are well analyzed by the author within the context of the agreement between Norway and Russia. The author points out that the Salukvadze compensated solution might be the best solution for this problem, because cooperation gives very high values with respect of non-cooperation, so that threat point are less important for the solution scheme. Moreover, it is necessary to make interpersonal comparisons, because there are many differences between Norway and Russia in terms of preferences. Thus, the Salukvadze solution seems to be the most adequate.

What about n-players?

So far, we have taken into account only models and real cases in which there are no more than two fishing agents. As mentioned above, new issues arise when it is necessary to deal with the management of straddling stocks. In such case, indeed, the number of the involved agents might be greater than two and can vary over time (however, it is important to notice, as Munro and Miller (2002) report, that the number of players dealing with fisheries issues is not generally much more than 4 or 5. This is an important point to understand why the research in fishery is often confined to a small number of agents involved).

It is important to notice that the problem is well known by the international community: in 1995, as mentioned above, there was a U.N. Conference on the management of straddling stocks suggesting cooperation through Regional Fisheries Management Organizations (RFMO)[5], where all countries interested in fishing in the region are allowed to participate and no one who is really interested in the resource can be avoided from exploiting it.

This is an attempt to solve the lack of property rights in the high seas, but it is not a real property regime since anyone can enter or exit form the RFMO. Moreover, this new framework leads to the new entrants' problem. This is the issue we want to address in the following section. Here we want to report the first approach dealing with fisheries management with more than two agents and to understand the problems arising for cooperation with more then two agents in the fishery.

Hannesson (1995) proposes a model such that it is possible to face the problem of sequential fishing. The objective was to introduce the problem of the stock externalities[6] that occurs when two or more agents fish sequentially a migrating fish stock. The author cites two examples: the Arcto-Norwegian cod stock and the Atlanto-Scandian herring stock. The first is addressed above, while the second will be addressed in the following section and it is a typical high seas fishery.

Hannesson structures the model for two harvesters fishing sequentially, but the structure of the model is such that it can be extended to n persons. He supposes to have two different fishing areas; in each of them there can be only one harvester, but the areas are linked by the migration of the fishery. We can think of a seasonal migrating fishery or of a fishery which has two or three different habitats depending on the age of the stock (typically, the Arcto-Norwegian stock has the spawning area in the Russia's EEZ, while the adults lives in the Norway's EEZ).

Hannesson defines two variables representing respectively the stock left in the first area after the harvest of the first fisher $\left(X\right)$, and the stock remained in the second area after the harvesting by the second fisher $\left(S\right)$. It is assumed by the author that the stock migrates at a certain time from area 1 to area 2, and then it returns again to area 1. The

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[5] An RFMO can be an organization of both coastal and distant water fishing nations in a region or in a sub-region

[6] As Grønbæk (2000) reports, it is possible to consider different kind of externalities:

- Dynamic and stock externalities: these are the externalities induced by the harvesters to a resource stock. While the dynamic externality is "*the bionomic loss, which arises when a single dynamic population is exploited by a finite number of fishers*", the stock externality occurs when "*harvest affects the total stock size and thereby affects other harvesters cost negatively as the resource stock is reduced*";
- Market externalities: these are externalities "*introduced by the market*"; in general, it affects the price of the fish. [See Sumaila, U. (1999). "A review of game-theoretic models of fishing", *Marine Policy*, vol.23, n°1, pp.1-10];
- Multispecies interaction externalities or biological externalities: "*The externality is caused by interdependency of species in the resource stock*". [See Sumaila, U. (1999). "A review of game-theoretic models of fishing", *Marine Policy*, vol.23, n°1, pp.1-10].

stock availability at time t is expressed as $G(S_{t-1})$ (where S_{t-1} is the stock left behind after harvesting in period t), and it depends on what is fished in the second area by the second fisher. The function:

$$G(S) = S\left[1 + a\left(1 - S/K\right)\right]$$

is the discrete variant of the logistic function, where a is the intrinsic growth rate and K is the carrying capacity.

It is quite obvious that there exists some kind of interaction between the actions taken by the two harvesters. Furthermore, we understand how this two-person, two-areas model can be extended to an n-person model. The time setting of the game is discrete and the game is repeated with an infinite horizon.

Assuming that the costs of unit effort are inversely proportional to the size of the stock and that the discount factor δ is the same for both players, Hannesson analyzes different situations depending on the relative effectiveness of the players. It is found that, allowing for side-payments, the situation is well known and implies that the most efficient harvester takes care of the resource and divides his gains with the less efficient harvester. If side-payments are not allowed, there is a room for bargaining on the agreeable harvest program following the model proposed by Munro (1979).

A series of cooperative and non-cooperative examples are offered by the author: what determines the outcome of the interaction are the initial size of the stock and the relative fishing effectiveness of the harvesters. Without binding agreements, what makes cooperation reachable is the threat of having less abandon level of the fishery then a lower stock level for future harvest. Thus, also in this case a threat regime is necessary to allow cooperation.

What is reported above is a particular case of a situation in which several agents are involved in harvesting a transboundary fishery.

Hannesson (1997) studies, with a hypothetical example, the possibility of cooperation in the management of transboundary fisheries, analyzing four cases:

1. when the agents are identical;
2. when the agents are different in terms of costs (effectiveness);
3. when the harvest deals with a limited migrating stocks (the previous analysis of Hannesson (1995) could be relevant here);
4. when the harvesters are facing a straddling stock.

The basic model is the following. Here again the time setting is repeated with an infinite time horizon (a *supergame*). Recalling $G(S_{t-1})$ as the growth function of the fishery, the amount caught in period t is expressed by $G(S_{t-1})-S_t$, and denoting with p the size of the fish, the revenue obtained form the resource in period t will be:

$$R_t = p\left[G(S_{t-1})-S_t\right].$$

Like in Hannesson (1995), the marginal cost of catch is considered inversely proportional to the size of the stock and the cost per unit of effort is assumed to be constant:

$$C_t = \int_{S_t}^{G(S_{t-1})} \frac{c}{x}dx = c\left[\ln G(S_{t-1}) - \ln S_t\right],$$

where c is a cost parameter and x is the size of the fish stock which is caught in period t.

The present value will be, for an infinite time horizon,

$$PV = \sum_{t=0}^{\infty} \delta^t \left\{p\left[G(S_{t-1})-S_t\right] - c\left[\ln G(S_{t-1}) - \ln S_t\right]\right\},$$

where δ is the discount factor. This present value represents the value of the resource in the case of cooperation. If the agents are identical, their share of the net revenue from the resource in each period of time is $1/N$ of the net revenue of the whole resource. Thus,

$$V^0 = \frac{\pi^o}{N}\frac{1}{1-\delta},$$

where $\pi^o = p\left[G(S^0)-S^0\right] - c\left[\ln G(S^0) - \ln S^0\right]$ and S^0 is the abandonment level of the stock along the optimal cooperative path.

It is possible that some agents deviate from cooperation. In such a case, it is assumed by the author that this behavior is discovered after one period of time. After this period, all the other harvesters play the punishment strategy against the free-rider fisher as much as they can, leaving the lower abandonment level of the stock.

The revenues gained from deviating are the sum of the profit of driving the stock down to the non-cooperative abandonment level (the bionomic equilibrium, $S^{\infty} = {c}/{p}$), plus the revenues that are possible when all the other harvesters punish the free-rider:

$$V^{d} = \frac{\pi^{0}}{N} + \pi^{d} + \frac{\pi^{*}}{N}\frac{\delta}{1-\delta},$$

where $\pi^{d} = p\left(S^{0} - S^{\infty}\right) - c\left(\ln S^{0} - \ln S^{\infty}\right)$, and $\pi^{\infty} = p\left[G\left(S^{\infty}\right) - S^{\infty}\right] - c\left[\ln G\left(S^{\infty}\right) - \ln S^{\infty}\right]$.

If defection from the cooperation is not profitable, these revenues for each agent are greater then the revenues that it can gain deviating from cooperation.

Thus, if V^{0} is the present value in the cooperative strategy for each agent in one period of time and V^{d} is the present value of the payoff for an agent that deviates from the cooperative solution, defection is not profitable if $V^{0} > V^{d}$, which implies:

$$N < \frac{\delta}{1-\delta}\frac{\pi^{0} - \pi^{*}}{\pi^{d}},$$

if $\delta \to 1$, the right-hand side approaches infinity and defection will never be profitable; for positive discount rate (that is, $\delta < 1$) "*the temporary gains from defecting may outweigh the long loss of playing non-cooperatively rather than cooperatively. How likely this is depends on N*".

Tthe author shows how self-enforcing cooperation depends on the discount factor, on the biological stock parameters (such as the intrinsic growth rate), and on the efficiency of the fishing fleets (remember that in this case the costs are the same for all the harvesters).

The incentives to deviate from cooperation increase with the number of agents exploiting the resource: "*Whenever stocks are fully contained within the 200-mile zone but migrate between different national zones, the number of countries with access rights is usually highly restricted*", thus cooperation might be possible with self-enforcing agreements. "*For the case of stocks located outside the 200-mile zone the conclusion is more pessimistic*".

Trigger strategies are considered here to avoid non-cooperation among the agents and it is showed that a lower discount factor makes the cooperative solution less likely: future return is weighted less and the deviation is preferred.

Cooperative solutions in fisheries' management

So far we have seen that there could be room for cooperation. It has been shown how it can be difficult to manage straddling stock fisheries. When many agents are involved in the exploitation of a straddling fishery, the number of the agents is crucial in order to reach cooperation. Moreover, it has been shown how it is possible that the problem to reach cooperation is overcame, allowing for side-payments, by using trigger strategies; in this case, the Nash bargaining scheme extended to a multiple-player game with infinite time horizon offers a unique point solution to the managing problem, sharing equally the net revenues from cooperation between the harvesters (of course, taking into account their threat points).

Leaving aside the trigger strategies, we now want to report some methods to address the issue derived from *coalitional game theory*. This theory is founded on the basis that agreements are binding and transfer payments are feasible. It is questionable if this is a real framework to develop the models, but taking into account what is stated in the 1995 U.N. Conference, these issues seem not so far from being realized. In fact, as mentioned before, the 1995 U.N. Conference signed the Agreement on Straddling Fish Stocks and Highly Migratory Fish Stocks. This agreement allows a partial resolution of the lack of property rights in the high seas; it imposes on the countries (coastal states and distant water fishing nations) reaching the agreement that the management of high seas fisheries must take place within a RFMO, follow sustainable principles, and that any one who wants to exploit the resource must agree on certain conservationist practices. In several articles, this agreement is considered binding, thus it is possible that cooperative game-theoretic schemes take place.

These games are called coalitional games or characteristic function games (Mesterton-Gibbons, 1992). In these games "*…the fishing nations have no bargaining power on their own. It is the coalitions that the countries can form with one another that define their contribution in the cooperative agreement and consequently their bargaining strengths. Thus it is natural that the result of the two-player c-game coincides with the Nash bargaining solution*". Thus, searching for a solution for transboundary fisheries' problems takes into account the coalitions and their bargaining strength in order to obtain cooperation. It is important to note that the strategic behavior of players forming coalitions is not considered in coalitional games, but the focus is on sharing the surplus from cooperation, that is, coalitions or the grand coalition are assumed to be formed.

The following game settings even allow introducing a grater awareness of the new member problems arose in managing straddling fisheries.

Kaitala and Lindroos (1998) and Li (1998) introduce coalitional games to solve the problem of high seas fisheries when there are several fishing nations involved. Kaitala and Lindroos (1998) structured a three-person coalitional game (of a hypothetical case) in which there are three nations harvesting a straddling stocks.

Li (1998) proposes a similar approach to address the sharing of the benefits of cooperation in a RFMO and, as we will see, gives some insights on the problem of new entrants.

In general, costs and bionomic equilibria differ between the agents. In the aforementioned papers this is the main difference between the harvesters. In Kaitala and Lindroos (1998) costs and bionomic equilibria are ordered as follows:

$c_1 < c_3 < c_2$ and

$x_3^\infty < x_2^\infty < x_1^*$.

Thus, the coastal state is the most efficient fishing nation, and its equilibrium level (x_1^*) is the optimal equilibrium level for the management of the resource; 3 follows 1 while the less efficient is 2. Following the reasoning in Appendix I, the resource is overexploited at the level x_3^∞ if non-cooperation prevails, level at which the most efficient coastal state can avoid other agents to take economic returns from the harvest.

Kaitala and Lindroos consider that agents agree to cooperate, that agreements are binding and that transfer payments are allowed. They suppose that the agents, following the structure of the game by Kaitala and Pohjola (1988), sold their quotas to the most efficient nation. Then the main issue is how to share the surplus from cooperation according to some fairness principles. This surplus is considered as the difference between what is gained from cooperating $\left(w\left[x(0)\right]\right)$ (in which the most efficient harvester acts as the sole-owner) and the sum of what is gained by each harvesters acting non-cooperatively $\left(\sum_{1,2,3} J_i\left[x(0), E_1^N, E_2^N, E_3^N\right]\right)$, here considered as the threat points (N indicates the effort strategies in the Nash equilibrium), and it is often indicated $e\left[x(0)\right]$:

$$e\left[x(0)\right] = w\left[x(0)\right] - \sum_{1,2,3} J_i\left[x(0), E_1^N, E_2^N, E_3^N\right] \quad (N \text{ indicates the Nash equilibrium}).$$

It is useful to spend few worlds explaining these revenues, borrowing from Li (1998). Suppose the grand cooperative stock agreement is not yet negotiated. We can calculate the surplus for each sub-coalition that can form with three players. For example, 1 and 2 can form the sub coalition $\{1,2\}$ and its additional fishery return would be:

$$e_{\{1,2\}} = w_{\{1,2\}} - \left(J_1 + J_2\right).$$

In this case, the less efficient 2 is bought out by 1 who dictates the harvesting policy for the sub-coalition as well as dominates fishing effort and total allowable catch. It is necessary that $e_{\{1,2\}} > 0$ in order to avoid the Nash feedback situation. However, it is necessary to compensate 2. The same reasoning is possible for all the other coalitions.

The coalitional game is a game that assigns to every coalition a value representing its revenues in cooperation. In order to contemplate the possibility of the presence of sub-coalitions, instead of the grand coalition, the characteristic function of the game is said *normalized*, meaning that the value reachable by any coalition is referred to as the payoff reached if the grand coalition has been formed. This form of the characteristic function game allows us to realize whether there is a real interest for the players joining any coalition to cooperate in the grand coalition. The characteristic function is:

$$v(K) = \frac{v^*(K)}{e\left[x(0)\right]},$$

where $K \in \left\{2^m - 1\right\}$ (with m being the number of the players and 2^m number of the possible coalitions of m players), and $v^*(K) = e\{k\}$ are the surplus benefits for the coalitions evaluated at $x(0)$. The greater the value of $v(K)$, the stronger the coalition's bargaining power (note that here the value for the grand coalition is 1). "*In other words, $v(K)$ is the benefit generated by the harvesting sub-coalition expressed as a proportion of the benefits generated in the grand harvesting coalition*. (Li, 1998)"

Reasoning on the relative fishing costs of countries involved and taking into account the possible coalitions, it is simple to understand that only for the coalition $K = \{1,3\}$ it is possible to have $v(K) > 0$, meaning that only this coalition has any interests in harvesting alone, without forming the grand coalition. This is due to the fact that x_3^∞ is not reached and the two more efficient countries can harvest alone until x_2^∞ is reached, leaving outside the third less efficient country.

These few considerations about coalitions are important in the sense that we can start to understand how necessary is their contemplation in order to raise the awareness of the likelihood of having cooperation. This is the field of coalition formation theory and we will briefly introduce it in the next section.

After this introductory analysis, which can be enlarged for more than two players involved, we can report the solution concept introduced to find a better solution for the players that allows for a better maintenance of cooperation following different fairness concepts: the egalitarian method, the Shapley value (Shapley 1953) and the nucleolus (Schmedler 1969).

While the first solution concept (egalitarian or Nash bargaining) is discussed in the previous sections and gives an equal share of the net benefits form cooperation to each player

$$w_i\left[x(0)\right]=\frac{e\left[x(0)\right]}{3}+J_i\left[x(0),E_1^N,E_2^N,E_3^N\right]\qquad i=1,2,3,$$

here we want to focus on the other two, which in some sense are fairer.

It is now necessary to determine an imputation vector $z=(z_1,z_2,z_3)$ that satisfies these properties:

1. $z_i \geq 0$ (Individual rationality);
2. $z_1+z_2+z_3=1$ (Group rationality).

The idea of the nucleolus is to find a payoff vector whose excesses[7] for all coalitions are as large as possible. This means that the benefit of the least satisfied coalition is maximized. In order to illustrate the fairness concept within the nucleolus, it is necessary to focus on the efficiency of the fleets. It is in fact shown in the literature that as the bargaining power of coalitions having it (because it is possible that no one coalition has bargaining power) decreases, the nucleolus approaches the egalitarian Nash bargaining solution. Thus, to perceive differences between this two solution concepts, it is necessary that the efficient nation has substantially better efficiency then other nations. The intuition is that "*...it is not fair to reward small differences in the contributions to the common benefit from cooperation*" (Kaitala and Lindroos, 1998). For this, nucleolus is also good for regional cooperation since it guarantees that the benefits shared by the solution are similar between more efficient and less efficient countries when the costs' differences are small; vice versa the differences in the benefits from cooperation are greater when there is more difference between the fishing costs of the countries involved (Kaitala and Lindroos, 1998).

It is demonstrated by Kaitala and Lindroos (1998) that the Shapley value takes into account the bargaining power of coalitions. By doing so it also addresses the fairness of the solution concept: the members of the coalition which has a biggest bargaining power receive more then other members outside this coalition. In fact, the authors computed that:

[7]Given a payoff vector, its excess for a coalition *S* is defined as the difference between the total amount offered to the coalition by this payoff vector and the value of the coalition *S*.

$$z_1^S = z_3^S = \frac{v(\{C, D_2\})}{6} + \frac{1}{3}$$
$$z_2^S = \frac{1 - v(\{C, D_2\})}{3}.$$

In Kaitala and Lindroos (1998), the agents involved are assumed to be:

- Country 1, a coastal state;
- Country 2 and 3, two distant water fishing nations.

Thus, using an appropriate sharing rule, it is possible to make all participants better off and to better guarantee the maintenance of cooperation.

In Li (1998), the agents involved are assumed to be:

- Country 1, a coastal state;
- Country 2, a distant water fishing nation;
- Country 3, a new entrant.

The game setting in the two papers is the same. Four important assumptions are made by the authors: first, the three nations are the only willing participants; second, there exists a complete information regarding the negotiating members' fleet efficiency; third, they face the same competitive market price, but differ in their harvest costs: $c_1 < c_2 < c_3$. Lastly, the optimal stock level x^* and the bionomic equilibrium x^∞ are ordered as follows:

$$x_3^* > x_2^* > x_1^* > x_3^\infty > x_2^\infty > x_1^\infty,$$

where "*the optimal stock level maximizes the resources rent through a most rapid approach path for the harvesting effort, and while the bionomic equilibrium fully dissipates the resource rent…*".

With this order, it is reasonable to postulate that the additional returns to various sub-coalition and grand coalition combinations satisfy the following:

$$e_{123} > e_{12} > e_{23} > e_{13} > 0.$$

Li (1998) asserts that this equation "*…also explains why the incumbents (1 and 2) would voluntarily allow the new entrant, 3, to join the club and negotiate for a grand coalition in the first place…*". If an appropriate fair sharing rule is worked out, it is possible to have that all the agents can gain from cooperation in the management, even including the new member.

The author assumes that the share of total benefits is increasing with the participant's fleet efficiency and the efficient fleets contribute more benefits to any sub-coalition involving them as the last joining members; the more efficient fleet also dictate the harvesting policy for the sub-coalitions, and for the grand coalition as well as fishing effort and total allowable catch (TAC); furthermore, the benefits from cooperation will increase with the number of participants.

These assumptions bring to the exact computations of the Shapley value and of the nucleolus.

Li (1998) proposes these computations for the solution above introduced:

Table 1
Exact Solutions for the Nucleolus, Shapley-Value, and Egaliatarian Imputations

x_i	Nucleolus Imputation		Shapley-Value Imputation		Egalitarian Imputation
x_1	$1/3 + (e_{12} + e_{13} - 2e_{23})/3e_{123}$	$\geq$	$1/3 + (e_{12} + e_{13} - 2e_{23})/6e_{123}$	$\geq$	1/3
x_2	$1/3 + (e_{12} + e_{23} - 2e_{13})/3e_{123}$	$\geq$ or $\leq$	$1/3 + (e_{12} + e_{23} - 2e_{13})/6e_{123}$	$\geq$ or $\leq$	1/3
x_3	$1/3 + (e_{13} + e_{23} - 2e_{12})/3e_{123}$	$\leq$	$1/3 + (e_{13} + e_{23} - 2e_{12})/6e_{123}$	$\leq$	1/3
Σx_i	1		1		1

Source: Li (1998), page 256

Solution schemes for the New Members problem

Before adding a real example, we now want to report the literature dealing with the new member problem. The hypothetical example proposed in Kaitala and Lindroos (1998) above focuses its attention on the sharing of the gains from cooperation in a way that is reasonable for the players, but the fishery can still be seen a shared fishery, although distant water fishing nations are also considered (see also Bjørndal, Kaitala, Lindroos and Munro (2000)). But as we have seen, there is also the new member problem which is not considered in that article. More generally, it is pointed out in Pintassilgo and Costa Duarte (2000) that "*the economics of the cooperative management of straddling and highly migratory fish stocks is still at an early stage of development*". The paper doesn't consider the potential instability generated by the number of players and there isn't a complete awareness of the right measures to avoid them; moreover, at 2000 the UN agreement on the management of straddling stocks through RFMOs was not even fully ratified.[8] This agreement creates a particular property right regime for which it is possible to eliminate one fishing nation from the fishery if it doesn't agree with the principles of sustainable harvest and recruitment of the stock. But no one can oblige that a new member really interested in the exploitation of the resource and respecting the duties of the agreement to remain outside of that.

Pintassilgo and Costa Duarte (2000) offer a review of what is done by 2000 to address this problem in a cooperative game setting. Kaitala and Munro in their paper (1993) showed that in a shared stock fishery the new entrants problem doesn't arise because the number of agents is fixed and very often composed by coastal states only, or at least by short distance neighboring states.

The focus in this analysis is on the threats new members pose to the cooperative agreements and the possible solutions to this problem. How can threats of new members act? First of all, we should say that threats have a temporal dimension, in the sense that they affect the stability of cooperation, both when a new member enters the organization, or if it is believed by the agents in the RFMO that a new entrant could be added to the agreement.

Kaitala and Munro (1997) argue that "*…when an RFMO is being established, the expected payoffs of cooperation may fall below the threat-point payoffs if a prospective new member must be admitted and must be given a share of the resource harvest*". They structured the threats assuming that the reaction to the breaking of the agreement when a new member enters the RFMO, is the formation of sub-coalition acting non-cooperatively. This problem arises when the expected payoff for the agents that join the RFMO with the new member are lower than the threat point of the initial members. Hence, Pintassilgo and Costa Duarte (2000) introduce an equation that allows determining which situation occurs when there is no cooperation with new entrants; the cooperative agreement will not be implemented if the following conditions are met for any of the original members:

$$P_{i,t}\left(x_t, S_i^N, S_{P\{i\}}^N\right) > P_{i,t}\left(x_t, S_i^C, S_{P\{i\}}^C, S_{NM}^C\right),$$

where $P_{i,t}$ = payoff of player i evaluated at period t; x_t = the state of the stock at period t; S_i^N = strategy of player i under non-cooperation; S_i^C = strategy of player i under

[8] The agreement came into force in December 2001. [Munro, G., Miller, K. (2002). "Cooperation and Conflicts in the Management of Transboundary Fishery Resources", *Proceeding of the Second World Conference of the American and European Associations of Environmental and Resource Economics*, June].

cooperation; P = set of players at period t; NM = new members. The authors point out that if the new entrants are “legally” allowed in the RFMO, this condition is very often verified.

This problem affects cooperation and brings to a non-cooperative management. The problem of the new member does not occur only at the beginning of the joint management with the RFMO, but if the agreement is not binding through time, there is a dynamic problem that undermines the cooperation and at each step in time the players must evaluate their position.

In literature are proposed three solution schemes to address the new entrant problem:

- Transferable membership: this scheme is developed with Individual Transferable Quotas (ITQs) and was proposed by Kaitala and Munro (1997). At first, the members of the RFMO establish the available total catch for the fishery. This available catch is then allocated in two stages: in the first the RFMO allocate the quotas between the countries involved, then each country allocate its quotas to the fishermen. Every nation interested in the fishery, must pass through the RFMO, thus it must buy quotas from the agents in the RFMO to harvest the fishery. We can think that this is similar to having a property rights regime, in which the RFMO establishes the TAC and the allocations of them. This method can avoid the problem of the new member because its appearance will not mean the dissipation of returns for the initial members. In fact, it does not affect both the cooperative and the non-cooperative payoffs of the agents in the RFMO. The quotas can be sold by each country to the other countries in the RFMO. This scheme is efficient, even for the maintenance and the recruitment of the stock, but due to the fact that quotas are sold in a public international market, multinationals can vanish the power of local fishermen and could cause loss of the local employment (with socio-economic repercussions);
- Waiting period: it was also proposed by Kaitala and Munro (1997). Assume that a cooperative agreement is signed for some period and that is binding through time. In this scenario, a waiting period is introduced (stop of harvest) that can delay the revenues for the new member and could reduce the payoff of the original members. This could rise the willingness to cooperate with the initial members of the RFMO; this is true as much as the discount factor of the agents is high, because with this the present value is very important and could lead to the free-rider problem. Thus, the effectiveness of this solution changes with the discount rate that nations exhibit. This scheme can also be an efficient solution for protecting binding agreements over time, but only if there are permanent high costs to stay in the fishery: even in this case, indeed, the discount factor plays an important role;
- Fair sharing rule: we have seen in Li (1998) that it is possible to consider a fair sharing rule so that the cooperation with the new entrant is useful in terms of payoffs for all the agents. Moreover, it is argued by Pintassilgo and Costa Duarte (2000) that if according to the sharing rule the most efficient agents receive more then the less efficient ones, there is an incentive for the less efficient interested in free-riding the grand coalition not to enter the fishery. With a fair sharing rule it is guaranteed that each player receives a payoff at least as high as its threat point. “*Thus, new members*

do not pose a threat to the cooperative agreement and the condition…" above mentioned "*…is not verified*". (Pintassilgo and Costa Duarte, 2000).

Two limits for this scheme are imposed by the same Li (1998): complete information is a necessary assumption, and as the number of players rise it is difficult to agree to a specific concept of fairness.

In Pham Do, Folmer and Norde (2001) it is proposed another method to address the new member problem. Their aim is to search an allocation that allows coalitions to be stable in a way that this is guaranteed even when a new member would join any coalition he wants. Thus, like Li (1998) they search for an allocation scheme that would guarantee some kind of fairness; here this kind of fairness is related with single coalition that has to be as greater as they can to arise the payoffs for its members. They propose the so called *population monotonic allocation scheme* applied to fisheries' revenues allocations. The idea is taken from Sprumont (1990).

Let $z_j(S)_{S\subseteq N,\, j\in S}$ be an allocation scheme; a coalition S is stable, in the sense that induces an additional agent to join it, if the additional benefit of player j when country k enters S is such that:

$$z_j\left(S\cup\{k\}\right)-z_j\left(S\right)\geq 0, \qquad \text{for all } j\in S.$$

If the allocation scheme satisfies this property, it is said that it satisfies the population monotonic allocation scheme[9]. It can be seen how guaranteeing that it is satisfied by a certain allocation scheme, means that new member and the agents of a coalition benefit from the new greater coalition.

In Pham Do, Folmer, Norde (2001) it is proved that fishery games (for the detailed definition of a fishery game we refer to the paper) have a population monotonic allocation scheme. Furthermore, the Shapley value calculated for each sub-game give the population monotonic allocation scheme.

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[9] The formal definition of the population monotonic allocation scheme is given in Pham Do, Folmer, Norde (2001):

Def.: *A vector* $\left(z_{i,S}\right)_{S\subseteq N, i\in S}$ *is a population monotonic allocation scheme for a cooperative game* $\left(N,v\right)$ *if it satisfies the following conditions:*

- $\sum_{i\in S} z_{i,S}=v\left(S\right)$ *for all* $S\subseteq N$ *;*
- $z_{i,S}\leq z_{i,T}$ *for all* $S,T\subseteq N$ *with* $S\subseteq T$ *and all* $i\in S$ *.*

Coalitional games to the management of a straddling stock fishery, the North-Atlantic Bluefin Tuna, and the new member problem (Duarte, Brasao and Pintassilgo, 2000: 21-36)

The North-Atlantic bluefin Tuna is a particular highly migratory fishery: the stock is divided into two spawning areas, one in the Gulf of Mexico and the other in the South Tyrrhenian Sea, in the Mediterranean Sea. These stocks migrate through the Atlantic Ocean: the first stock from West to East, while the second from East to West. This situation generates the presence of two different stocks, the western stock and the eastern stock of bluefin tuna. The states involved in the harvest of two stocks are different, but we can say that there are three agents for both the stocks: the western stock is harvested by USA, Canada and some distant water fishing nations, while the eastern is harvested by EU (European Union), OCS (Other Coastal States) and some distant water fishing nations.

It is possible to construct a game setting very similar to the one in the theoretical papers by Kaitala and Lindroos (1998) and by Li (1998). Costa Duarte, Brasao, Pintassilgo (2000) separate the analysis of the management and the result from cooperation into two parts. However, they demonstrate that the differences between the two analyses are not much. Thus, there are two RFMOs and the agreements are supposed binding.

They propose a model that permits the simulation of possible outcomes of the considered fishery based on a multi-gear, age-structured, bio-economic model developed ad hoc for this fishery in another paper (Pintassilgo, Brasao and Duarte, 1998). The optimization method of the model permits the computation of the optimal strategies of the countries involved in the harvest. The real case implies one main difference from the theoretical structure: "*…the players do not differ in costs (or efficiency), but in dimension and composition of gear structure*". Hence, the bio-economics model of the fishery is structured taking into account that different fishing gear target different quality and size of bluefin tuna, which also have different market values. Each of the agents interested in the tuna fishery has a particular gear's composition, thus it has its particular advantages to harvest using a certain harvesting program obtaining a certain catchment value.

The optimal strategies are assumed to be fixed strategies maximizing net present value of profits over 25 years. These strategies are defined as effort reduction of gears for each coalition that can be formed by the countries involved, and also for the grand coalition. Then, they calculate shares of the gains from cooperation with three different cooperative solution concepts: the Nash bargaining solution, the Shapley value and the nucleolus.

The findings suggest that every solution concept gives a unique solution point, but none of them lies in the core, meaning that some players can do better by free riding the grand coalition. In fact it is showed that some of the states involved could gain more in a two-member coalition that in the grand coalition, furthermore the coalition which includes the EU has a bargaining power and each of its players could be better off without the grand coalition. This leads to the free rider problem, avoidable if we are in a RFMO regime. But this is true only for the DWFNs, not for the coastal nations which can continue to fish within their EEZ without incurring in any restriction by the RFMO. This result has not been found by the theoretical papers mentioned above.

The sharing of the gains from the grand coalition is equal for the nucleolus and for the Nash bargaining solution, "*this is due to the low value of the gains for all the two-member coalitions*"[10]. It is different for the Shapley value, which "*reflects the average contribution of each player in the set of possible coalitions…*". Hence, this paper (Costa Duarte, Brasao, Pintassilgo (2000) confirms what is found in the theoretical paper previously mentioned. But, as said before, in this applied case no allocation lies in the core. Thus, it is difficult to choose which kind of solution concept is better.

As introduced above, Pintassilgo and Costa Duarte (2000) studied the new member issue referring to all of the approaches presents in literature at that time. After a theoretical explanation, they applied the three solution schemes to the North-Atlantic bluefin tuna fishery assuming that a RFMO is established for its cooperative sustainable management.

They found that, due to the scarcity of the tuna stocks, it is always inefficient to have a non-cooperative exploitation of the resource: "*the threats of the new members are not sufficient for the breakdown of the cooperative agreement*". This is true at the beginning of the negotiation, when the RFMO's members can evaluate in advance the options associated with cooperating or not.

If the agreement is not binding, this is a problem the members of the RFMO face through time, which does not go away with the initial decision to cooperate. It is shown that the transferable membership, through an ITQ system, is the most efficient scheme to solve the new member problem because it creates a change in the gear composition that is more favorable in terms of stock preservation.

Coalitions in fisheries

We have seen that some approaches take into account the formation of coalition since it is possible to have many players involved in a fishery management. Furthermore, some of these approaches briefly analyze what is the likelihood of having several coalitions rather then the grand coalition. In this section we address this issue.

A first attempt was proposed by Lindroos (1998). He reviews the game setting introduced by Kaitala and Lindroos (1998) and uses the coalitional approach to study a particular coalition formation process when the number of countries involved increases (above three). An important assumption that he makes is that the coalition formation is *restricted*. With this statement he wants to model the formation of coalition between nations having common interests in exploiting a fishery resource.

Suppose there are 2 DWFNs (D_1, D_2) and 2 coastal states (C_1, C_2). The restriction imposed is that the only feasible coalitions are $\{D_1, D_2\}$ and $\{C_1, C_2\}$. The value of a forbidden coalition is zero in the characteristic function. Then, they analyze three cases in

[10] In Costa Duarte, Brasao, Pintassilgo (2000) it is verified with real data what was explained by Kaitala and Lindroos in 1998. Kaitala and Lindroos, indeed, showed that as the bargaining strength of a coalition decreases, the nucleolus approaches the egalitarian imputation (see Kaitala and Lindroos, 1998, pp.289-291)

which there are differences in the efficiency of the single harvesting states and in the bionomic equilibria between the states. Comparing unrestricted and restricted Shapley value for each single state, if the DWFNs are inefficient enough, they refuse to form coalitions with the coastal state. The concept of feasible coalitions was originally created by Loehman and Whinston and was called Modified Shapley Value (Loehman and Whinston 1971, 1974, 1976).

In the first case it is assumed that:

$c_{C_1} < c_{C_2} < c_{D_1} \le c_{D_2}$ and $x^{\infty}_{C_2} < x^{\infty}_{D_1} \le x^{\infty}_{D_2} < x^{*}_{C_1}$. This assumption implies that the coastal states are the most efficient nations and that C_1 should be choosen as a result of a strategy.

Sub-case $c_{D_1} = c_{D_2}$ and $x^{\infty}_{D_1} = x^{\infty}_{D_2}$. If restricted coalitions are allowed, the only coalition having a bargaining strength is the "coastal states" coalition $\left(v\left(\{C_1, C_2\}\right) > 0\right)$, while in the unrestricted situation, also $v\left(\{C_1, C_2, D_i\}\right) > 0$. It is showed that in this case the restrictions in the coalition formation benefits the DWFNs because they Shapley value gives them more that in the unrestricted case; thus, the countries with less efficiency could improve their negotiation position through the restriction for coalitions;

Sub-case $c_{D_1} < c_{D_2}$ and $x^{\infty}_{D_1} < x^{\infty}_{D_2}$. In this case there are differences between the DWFNs. it is showed that in this case the distant fishing nation which is more efficient could gain cooperating with the coastal states.

2. $c_{C_1} < c_{D_1} \le c_{C_2} \le c_{D_2}$ and $x^{\infty}_{D_1} \le x^{\infty}_{D_2} \le x^{\infty}_{C_2} < x^{*}_{C_1}$. C_1 and D_1 "*are veto-players in the sense that both countries are needed for a particular coalition to have positive worth or bargaining strength*".

Sub-case $c_{D_1} = c_{C_2} \le c_{D_2}$ and only $v\left(\{C_1, D_1, C_2\}\right) > 0$; it is shown that the DWFNs could be better off by restricting coalition formation, because the difference between the unrestricted and the restricted Shapley value is positive;

Sub-case $c_{D_1} < c_{C_2} < c_{D_2}$ and $v\left(\{C_1, D_1, C_2\}\right) > v\left(\{C_1, D_1\}\right) = v\left(\{C_1, D_1, D_2\}\right)$. It is shown that the situation is the same as in the previous bullet;

Sub-case $c_{D_1} < c_{C_2} = c_{D_2}$ and $v\left(\{C_1, D_1\}\right) > 0$. It is shown that DWFNs are indifferent between restriction and unrestriction. Individually, it is more profitable to D_2 to restrict coalition formation than it is to D_1.

3. $c_{C_1} < c_{D_1} \le c_{D_2} < c_{C_2}$ and $x^{\infty}_{D_1} \le x^{\infty}_{D_2} < x^{\infty}_{C_2} < x^{*}_{C_1}$.

Sub-case $c_{D_1} < c_{D_2} < c_{C_2}$; it is showed that DWFNs are worse off by restricting coalition;

Sub-case $c_{D_1} = c_{D_2} < c_{C_2}$; it is the same as before.

After this first analysis, the author tries to simulate the situation where the number of players increases, showing that the results reported before can be applied to the n-player case; thus, a group of DWFNs is able to increase their bargaining strength by coalition restrictions.

Having in mind that the management of a highly migratory fish stock necessitate that all the nations involved must agree on a RFMO. It is clear that this problem introduces many difficulties in the joint management and might involve an incentive to free ride the agreement.

The coalitional analyses are very important in the context of an international negotiation process aimed to reach a cooperative agreement for the exploitation of a certain fishery, which is the process to reach a RFMO. In such a case, all interactions among states are possible and it is necessary to understand the behavior of the agents involved is in order to realize a cooperative exploitation.

In order to analyze what is done in the literature to solve this negotiation, it is useful to report here further insights given by Pham Do, Folmer, Norde (2001). This is a theoretical contribution, but gives some new ideas on how to solve the issue.

Pham Do, Folmer, Norde (2001) propose a particular game setting in which the sustainability of the allocation method is guaranteed by the statement (given through a definition in the paper) that for a fishery game there should be a "conservation strategy space" such that the sum of the strategies (here the control variables are the harvesting efforts) chosen by harvesters is less then the carrying capacity of the fishery. If the carrying capacity is overcame, the fishery stock decreases quickly. Moreover, they show that if total effort exceeds $b/2$, "*total profit is smaller than the maximum profit. The management problem comes down to the reduction of the harvesting level*". The rule they propose is the following:

Let $\left(x_i^*\right)_{i\in N}$ *be a competitive equilibrium. Define the proportional rule,* $PROP(i)$ *applied to every player* i *such that:*

$$PROP(i) = x_i^*\left(\frac{M}{x^*(N)}\right), \textit{ where } M = b/2 .$$

Thus, it is proposed to apply a proportional rule to allocate the harvesting shares among the agents involved, taking into account a sustainable concept for the resource, by which each agent can be better off.

Another important reference about the effects of coalition in fisheries' management is Lindroos (2002).

The Norwegian spring-spawning Herring Fishery

Bjørndal, Kaitala, Lindroos and Munro (2000) report an example of a specific case of straddling fishery that is the Norwegian spring-spawning herring. This fishery spawn within the EEZs of Norway and Russia; then it migrates towards Faroes passing through Iceland (North-Atlantic) water and closing the so called Ocean loop.

This stock showed large oscillations during the time due to strong harvest; there were different period of decline and of recruitment of the stock and there is a rich history on the relationships between coastal states (Norway and Russia), while it is difficult to find collaborations between coastal states and DWFNs (for further details, see Bjǿrndal, Kaitala, Lindroos and Munro (2000)).

The Ocean loop is one of the most important examples of the need to have cooperation through RFMOs, like the UN 1995 Agreement states. It is indeed demonstrated that "*the recovery of the Norwegian spring-spawning herring stock offers the opportunity for a substantial annual harvest on a sustainable basis for the benefit of all nations involved. It is clear that the present situation gives rise to international competition for shares in the herring fishery that might be biologically, economically and politically damaging if the agreement between the countries involved would collapse*". It is clear how there are strong incentives for the agents to overexploit the resource when it is passing through their EEZ.

We now want to report some insight given by Lindroos and Kaitala (2001). The paper analyzes the possibility of cooperation between countries sharing the Norwegian Spring-Spawning herring fishery. Several countries are involved. Norway and Russia, which are the most important coastal state for this fishery because their EEZs are the spawning area for the herring stocks, and other DWFNs (European Union and Iceland). The biological recruitment of the stock is modeled within the framework of the Beverton-Holt model, i.e. a cohort model. These kinds of models are difficult to implement because of their data needs, but in the case of the Atlanto-Scandian spring-spawning herring there is a good literature that offers such information (Patterson 1998).

The authors start within the analysis proposed in Arnason, Magnusson and Agnarsson (2000) and Lindroos (2000), but propose an extension by letting the fishing mortality vary along with fleet size and costs.

The net present values for countries, as a function of the control variables f and N, are given by:

$$J^i\left(f^i, N^i\right) = \sum_y \frac{pY_y^i - Q_y^i}{\delta_y},$$

where, f^i denotes the fishing mortality for country *i*; N^i is the number of fishing vessels of country *i*; *p* is the price of the fish; Y_y^i is the catch of country *i* in the year *y*; Q_y^i are the costs for country *i* in the year *y* (note that in the proposed cost function depends upon the catchability coefficient) and $\delta_y = \left(1+r\right)^{y-y_1}$ is the discount factor, where r is the discount rate. The function of the net present value depends on several parameters such as mortality, stock recruitment, number of vessels, selectivity of the fishing gear, costs of gear.

Introducing the catchability coefficient into the model, it is shown how this coefficient affects the possibility to agree on cooperation and to establish a grand coalition. The authors consider two different situations with two different catchability coefficients, high and low.

The authors construct the characteristic function of the game that assigns a value to each coalition (or union of countries). They consider at first the situation in which the catchability coefficient is high.

The characteristic function is as follows:

$$v(i) = J^i\left(F_N^i\right)$$

$$v(i,j) = J^{i,j}\left(F_N^{\{i,j\}}, F_N^k\right)$$

$$v(M) = J^1\left(F^*\right),$$

where $v(i)$ is the value of a single-player coalition; $v(i,j)$ the value of a two-player coalition; $v(M)$ is the value of the grand coalition. Term F_N^S denotes the strategy chosen in Nash equilibrium by coalition *S*, and F^* denotes the optimal full-cooperative strategy that maximizes the value of the grand coalition.

Three situations are presented: the first when the countries play a three-player non-cooperative game as single-coalition. The net present values for these countries are calculated with the characteristic function and it is showed that in this situation their gains are low and became negative after three years; the herring stock is rapidly driven to extinction. The study is done using the Nash reaction curves (these are also referred as best reply curves) and two basic concepts of coalition stability: the core and the individual rationality.

The second case is when the countries create two-player coalition. The paper adopted the Chander and Tulkens (1995) approach in which the country outside the coalition will play non-cooperatively against the coalition members. All the possible combinations are simulated. It is demonstrated that this is a more stable situation because the net revenues for the countries involved are higher that in the first situation. The stock will stabilize at a positive value in all two-player coalition cases. However, the spawning stock biomass is below the safe minimum biological level. In this case the reaction functions of the couples of players are simulated also. Finally, the full cooperative situation is studied and the net values for this coalition are calculated.

It is shown by the authors that the two-player coalitions are stable, but others are not. Even the grand coalition is not stable, the authors say, since the sum of the revenues accruing to its members, if they free ride, is higher than the value of the grand coalition.

The authors say also that the Shapley value is not in the core and that it is not reasonable to calculate the nucleolus "*since the equilibrium cooperation structures are two-player coalitions*" (while the nucleolus assumes that the grand coalition is formed and its revenues are shared among the players).

Now the case of low catchability coefficient. When there are single player coalitions it is demonstrated that some countries may have better payoffs and the spawning stock is above the safe level. When there are two-player coalitions, the relative difference between equilibrium strategies is greater and there is a significant biological difference between the two-player coalitions Nash equilibria. As compared to the high catchability coefficient case, the spawning stock is always above the safe level. In this case the full cooperation is possible because the sum of the outside coalition net present value is smaller then the benefits from full cooperation. Here the Shapley value is in the core. The nucleolus is studied using the Kohlberg's criterion (1971)[11].

The authors analyze also the new member problem. According to the UN agreement (1995), any country having real interest in a high-fishery must be allowed to join the RFMO. With respect to this problem, it is shown that the differences in catchability coefficient lead to very different situations. Suppose that there is a country interested in joint a fishery managed by an existing RFMO. Then the country can chose to enter it or to stay outside the coalition. If the coalition is constituted by two members, it is demonstrated above that this coalition is stable both externally and internally, because the members don't desire a new member enter the coalition and the new member finds no profitable to joint it. However, it could be useful and better for the coalition to buy the new entrant free-rider value to gain more then having to compete with him. In this case the new member has a great power and could gain money without making any actions, just pretending to be interested in the fishery. If a RFMO doesn't exist, the situation is more difficult for cooperation because some countries may find it optimal to wait before signing the agreement. In the other case, the grand coalition is stable because the new member has an incentive to join the cooperative organization.

An approach using linear programming

We now introduce a completely different approach to the fisheries' issue. Bardarson (2003) proposes a linear harvesting game with static multi-agent and multi-species fisheries. The motivation for using heterogeneous fisheries is, to demonstrate that heterogeneity may promote cooperation, if it is treated properly by the allocation mechanism. The participating agent $i \in I$ (set of players) could harvest his share of resource $s \in S$ (set of species). Each agent could harvest with a certain fleet $f \in F$. Thus

[11] "*The idea of the criterion is to have equal excesses for a balanced set of coalitions. In this case, it turns out that the excesses of the singletons are the lowest; thus the singletons are the most dissatisfied coalitions*". [Kohlberg, E. (1971). "On the nucleolus of characteristic function game", *SIAM Journal of Applied Mathematics*, 20, pp.62-66]

each agent's fishing effort is given by e_{sfi}, while each agent's catch per unit effort from fleet f, harvesting species s, is q_{sfi}.

Any coalition $C \subset I$ may pool the quotas and the harvesting capacities of its members, generating the optimal value with:

$$v_C = \max_{e_{sfi}} \left\{ \sum_{i \in C} \sum_{s \in S, f \in F} \pi_{c_{sfi}} e_{sfi} \mid \sum_{f \in F, i \in I} q_{sfi} e_{sfi} \le b_{sC} \forall s \in S, \sum_{i \in C} e_{sfi} \le \overline{e}_{sfC} \forall s \in S, f \in F \right\}$$

This function "*generalizes Owen's production function game by allowing variation in objectives and technologies/skills across agents*". After the definition of the characteristic function, the author implements the core allocation solving the dual program and finding the shadow prices that, as in Owen (1975), are useful to identify core allocations of the grand fisheries coalition. A theorem demonstrates that shadow prices yield core solutions.

With this linear programming application, the author says that it is possible to see that the coalitions are better off allowing substitution possibilities. Moreover, "*the shadow prices define a payment scheme (a contract) that provides all potential contributors with sufficient incentives to participate*". Transferable membership is considered a useful mechanism to avoid the problem that inefficient fishermen create for the resource management. "*As compensation it receives side-payments that at least match foregone income*".

Acid rain

Acid rain is another important transboundary environmental problem due to the sulphur and nitrogen emissions. Those pollutants are emitted in several industrial processes involving combustion; another important source is car traffic. Nitrogen oxides are produced in the combustion process and emitted to the atmosphere, while sulphur oxides derive from the impurities within the combustible.

These chemical substances react in the atmosphere forming acid rain that, falling with wet deposition, creates several problems affecting directly soil and indirectly forest growth. Obviously, other problems are created by the acid rain, but the most studied is the forest growth one. The acidification of soil changes its chemical and physical properties, involving changes in the transfer process of the nutrients from the soil to the plants. These processes affect forest growth.

All these processes are induced either in the boundaries of the emitting country, or outside the boundaries in the neighboring countries, due to the transport in the atmosphere. Thus, it is clear that those emissions create an international problem and environmental externalities, and it is easy to understand why is there a room for Game Theory.

In this section we review several contributions that address the acid rain problem through the CGT. The first important contribution is by Mäler (1989), who introduces four main issues related to acid rain:

- the uncertainty of the information on causes and effects;
- the use of a common pool resource in an asymmetric way;
- the game structured to solve the acid rain problems is of incomplete information about several economic parameters needed for the analysis;
- the parties involved don't agree on certain rules to solve the game.

One of the main important contributions of this paper is the approach taken to model deposition in the countries affected by the acid rain. Many papers in the literature use this approach schematizing the acid rain problem, but also to study several other problems of transboundary pollution.

If E_i are the emissions produced in country i and E is the vector of emission levels of all the countries, Q_i are the deposition in country i and Q is the vector of sulphur deposition in the countries, a_{ij} are the transfer coefficients representing the ratio of pollutants emitted by country i (E_i) and deposited in country j, and A is the transfer matrix including all the a_{ij} elements, the steady state model for the transport of sulphur is:

$$Q = AE .$$

The effects of the acid rain are expressed as a function of the deposition in each country:

$$D_i(Q_i);$$

These are damage costs functions. There is strong asymmetry in these games, due to the difference in emissions of the countries and also to the asymmetry of the transfer matrix, whose components depend on the meteorology (especially, winds) of the area under study.

The model is structured assuming full information about the economic variables; we will see how other papers assume different conditions. This is in fact a strong assumption on the available knowledge of the control and damage cost functions and of the depositions; very often it is not possible to know their value for the entire period, but rather to have only "local" information available.

The paper compares the Nash equilibrium's emissions and the full cooperative solution. The full cooperative solution is a particular case of Pareto-efficient outcome. The computation of the benefits from cooperation is computed allowing for side-payments (full cooperative solution) and disregarding side-payments (only Pareto-efficient outcome).

The economic problem in the full cooperative outcome is the following:

$$\min \sum_i \left[C_i(E_i) + D_i(Q_i) \right],$$

subject to $Q = AE$.

It is assumed in fact that, even if countries don't agree on certain arrangements, they would minimize the overall damage and control costs. The reason for choosing the minimization of the total damage and control costs "*is that this would yield a maximal surplus which could be distributed among the countries in some way…With no side-payments, the interests of the countries are much more in conflict with each other*".

It is shown that both Pareto-efficiency and full cooperative solution guarantee a better outcome for the nations involved. In the case of only Pareto-efficiency, total benefits are decreased by a certain amount, due to the fact that in the Pareto-efficient outcome it is not possible for some countries to be worse then in the Nash equilibrium outcome, while it is in the full cooperative case, due to the feasibility of side-payments.

It is necessary to recall that in this model control and damage costs are assumed to be deterministic, but they should be considered expected values, due to the uncertainty in their values.

The simulation is done assuming that in the initial situation, there is a Nash equilibrium, where the damage function are linear and "*can be calibrated such that the marginal damage cost is equal to the marginal control cost divided by the transfer coefficient* a_{ii}", that is, only those contributions are considered due to the local emissions for the same country. Thus, the damage functions are evaluated on the basis of revealed preferences deduced from what governments make on the damages in their countries.

An important assumption is that the utility is measured in monetary terms and that the costs have the same meaning for all the countries. "*This requires that the exchange rate is an equilibrium one and the cost of capital is the same in all countries*".

As we have said, the acid rain problem regards the acidification of soil. In several papers the economic methodology to address the problem is supported by an acidification model: that is, a model describing, in a simple way, the evolution of the chemical and physical features of soil due to the acid rain depositions.

Kaitala, Pohjola and Tahvonen (1991) propose a model that explains the soil acidification as a function of emissions and depositions; this acidification is quantified through the base saturation, which is the measure of the base cations (ions having positive charge) in the soil: as acidification proceeds, the base saturation decreases.

The components of the model are: $x_i(t)$, which represent the base saturation at time t in country i; $e_i(t)$, which is the total emission of sulphur in each country; d_{ij}, which is the sulphur deposition in country i originating from country j; d_{bi}, denoting the background depositions in each of the countries.

The base saturation dynamic depends on the sulphur depositions from emissions of the neighboring countries, through the transport coefficients, and on the background depositions, representing the natural state of the process in each country.

Emissions and depositions are connected through the following relation:

$$d_{ij}(t) = a_{ij} e_j(t),$$

where a_{ij} are the transfer coefficients introduced above.

Thus, total depositions can be expressed as follows:

$$D = AE + D_b,$$

where D are the total depositions in all the involved countries, A is the transport matrix, E is the emissions vector, and D_b are the total background depositions.

Then, they propose a long-range sulphur transport model that describes the long range transportation of emissions between the countries (Finland and USSR). The function to maximize is the following:

$$J_i\left(x_0, e_1, e_2\right) = \int_0^\infty e^{-r_i t}\left(U_i\left(x_i\right) - C_i\left(e_i\right)\right)dt\ ,$$

subject to the acidification dynamics and the relation between the emission and deposition (which is assumed linear here).

Emission abatement costs are assumed to be piecewise linear and are approximated by a quadratic a function of the emission reduction in each country:

$$C_i\left(e_i\right) = \beta_{i1}\left(\overline{e}_i - e_i\right) + \beta_{i2}\left(\overline{e}_i - e_i\right)^2 + \beta_{i3}\ ,$$

where the two β are constants and $\overline{e}_i$ denotes the emissions in absence of emission abatement efforts.

The benefit functions $U_i\left(x_i\right)$ derive from the quality of soil, because are expressed in terms of the base saturation affecting forest growth. The decline in forest growth is approximated by the following logarithmic function, which in general is an expression of a saturation process:

$$g\left(x\right) = \overline{g}\ln\left(\frac{x_i}{x_0}\right),$$

depending on the ratio between the actual value of base saturation and a reference value, assumed to be a small number; $\overline{g} = 1/\ln\left(x_n / x_0\right)$, where x_n is a level at which base saturation has no detrimental effects on the forest growth, that is $g\left(x_n\right) = 1$.

The benefits are expressed as follows:

$$U_i\left(x_i\right) = \gamma_i g\left(x_i\right),$$

where γ_i is the value of the forest growth in country i under normal conditions ($x_i = x_n$). It is more difficult to estimate the benefits since it is difficult to estimate the link between forest growth and base saturation, and consequences cannot be estimated with the same accuracy.

The games associated with the processes are non-cooperative and cooperative, and are differential games with an infinite time span. The solutions are provided by the first order optimality conditions and give the optimal emissions levels maximizing the single objective function, in the non-cooperative game, while the sum of objective functions is maximized in the cooperative case.

In the non-cooperative case, the target emission level does not take into account emissions in the neighboring countries, while in the cooperative case it takes into account the forest growth in the neighboring countries. "*…in cooperation the countries do reduce emissions more than in non-cooperation*".

In the two-country (USSR and Finland) simulation proposed by the authors it is shown that the USSR loses from cooperation. This means that in order to negotiate a cooperative agreement, there should be some transfer payments from Finland to USSR.

Kaitala, Pohjola and Tahvonen (1992) propose a similar approach, but introduce a different cost function, which is now quadratic instead of linear. The authors justify this new function by the necessity to have a better approximation of the Soviet abatement cost, which is supposed to have two different components: "*a linear segment describing the abatement costs for initial reductions of the emissions…and a quadratic segment*". The paper concludes that several other problems are due to the acid rain directly, such as abundance of fishes in the lakes, or indirectly, such as the landscape value of the forests.

Further research on the acid rain problem is developed looking for a model that should be able to describe the international cooperation through a particular transfer payments mechanism, and allowing for more than two agents. Kaitala, Mäler and Tulkens (1995) The basic structure is the model proposed by Mähler (1989), but to the economic-ecologic model is associated the game structure introduced in Tulkens (1979), i.e. allowing local information not full information, and assuming transfer payments with the sharing formula developed by Chander and Tulkens (1992, 1993).

The model is constituted by: $E = \left(E_1,...,E_n\right)^t$, countries' emissions; $Q = \left(Q_1,...,Q_n\right)^T$, depositions; $B = \left(B_1,...,B_n\right)^T$ background depositions in n regions. $A = \left(a_{ij}\right)$ denotes a transportation matrix. Depositions are linked to emissions through the function: $Q_i = \sum_{j=1}^{n} a_{ij} E_j + B_i$.

The costs for each country are defined as: $J_i = C_i\left(E_i\right) + D_i\left(E\right)$, where $C_i\left(E_i\right)$ denote a function that associates the total costs of aggregate productive activity in region i, with the level of emissions E_i taking place there. $D_i\left(E\right)$ denotes the total costs entailed in a country i by the damages caused by the depositions.

The optimization problem to solve is the following:

$$\min_{E_1,\dots,E_n} J_i = \sum_{i=1}^{n} \Big(C_i\left(E_i\right) + D_i\left(Q_i\left(E\right)\right) \Big),$$

such that $Q_i = \sum_{j=1}^{n} a_{ij} E_j + B_i$ is satisfied. It is assumed that the solution to this problem exists and is unique.

At this point, the authors introduce the Tulkens (1979) result which allows the substitution of full information with local information (that is, only the current values of countries' marginal emission abatement and deposition damage costs are considered): the optimum is not reached immediately, but through a path that "converges" to the optimal solution.

After this first economic analysis, the authors introduce the games associated with the economic model. Countries are willing to participate to an agreement if they can gain more in cooperation than a the Nash equilibrium.

The willingness is indeed measured with the difference between the gains in these two situations:

$$J_i\left(t\right) = \tilde{J}_i\left(t\right) - \overline{J}_i ,$$

which denotes the gain for region i at time t, where $\overline{J}_i$ are the costs in the Nash equilibrium (constant with respect to the time), and $\tilde{J}_i\left(t\right)$ are the costs at time t. For all countries involved, total gains are $J\left(t\right) = \sum_i J_i\left(t\right)$.

These costs are decreasing in time; this is demonstrated in the paper and the function that expresses the derivate is:

$$\dot{J} = -\frac{1}{K} \sum_{i=1}^{n} \dot{E}^2 \leq 0 ,$$

with $J\left(0\right) = 0$ ("*changing the value of K corresponds to changing the time scale such that increasing K makes the speed of emissions changes increase*"). At this point, the authors give some adjustments to the model to consider the possibility of cooperation among the countries involved in a transboundary pollution problem. It is possible that this function implies that $\dot{J}_i < 0$. Thus, one country might find this solution not individually rational for him.

The authors propose a transfer payments mechanism to solve this problem, that is to compensate the losses of the countries with increasing costs function. For each State, the function to maximize now is:

$$J_i + T_i = C_i\left(E_i\right) + D_i\left(Q_i\left(E\right)\right) + T_i\,,$$

with the constraint $\sum_{i=1}^{n} T_i = 0$ (feasibility condition). Transfer payments are introduced to solve a problem that cooperation induces, that is the violation of the individual rationality condition. They describe also the transfer payments mechanism, which takes into account the abatement cost sharing parameter introduced by Chander and Tulkens (1991).

This mechanism provides also coalitional rationality: "…*the cooperative game theoretical property of inducing an imputation in the core of local games associated with each point of the solution…The cooperation thus achieved is claimed to be stronger because it is not only individually rational but also coalitionally rational or group rational*".

The authors offer also another extension of the first model, introducing a non-linear damage function that considers the possibility of increasing marginal damages:

$$D_i\left(Q_i\right) = \frac{1}{2}\pi_i Q_i^2\,,$$

where π_i are the marginal damage costs of country i. With this new assumption, "*total reductions are less important than those obtained with linear damage functions, as one could expect*".

The paper proposes an application with real data to the problem of acid rain involving Finland, Russia and Estonia and uses their economic data to implement the computation.

The main result of the paper is that, as the authors say, "*local information is sufficient for determining a succession of cooperative emissions abatement programs that converge to the international economic Pareto optimum*".

Another dynamic approach is given in Mäler and de Zeeuw (1998). In this paper the authors consider the problem of acid rain taking into account the critical loads of the soil. The critical load is defined, from Nilsson (1986), as the maximal exposure to some pollutant an ecological system can adjust to without suffering long term damage. The acid rain problem affects many countries in this way: the soils have a natural buffer stock that can avoid the acidification problem, but this capability is not infinite and the buffer stock can be depleted. This depletion can be irreversible or reversible depending on the critical load, which is a feature of each soil. "*The more and the longer depositions exceed* *critical loads the higher the damage*" (page 167). Moreover, these emissions cross borders and what is produced in one country affects neighboring and distant nations. Given the features of the problem, the decision problem of the countries are dynamic optimization problems with a *stock variable*. The game to analyze these problems is a differential game.

The structure of the decision problem is the following: e_i denotes the emissions of each country $i = 1, ..., n$. It is given a transport matrix *A* where the element a_{ij} denotes the fraction of e_j that is deposited in country *i*. $A\mathrm{e}$ is the vector of depositions in the *n* countries derived from the emissions of the same *n* countries. d_i denotes how much damage is done to the soil and it is the depletion of the buffer stock, arising if a deposition goes above the critical loads for that soil. There are also background depositions: these depositions are due to the activities of the countries outside the group and to the sea; these are considered given in the model. If background depositions exceed the critical load in one of the countries, the group cannot control the acidification process in that country, but this case is not analyzed in this paper.

The decision problem is:

$$\min_{e_i} \int_0^\infty \mathrm{e}^{-r_i t} \left[C_i \left(e_i \left(t \right) \right) + D_i \left(d_i \left(t \right) \right) \right] dt, \qquad i = 1, ..., n$$

such that:

$$\dot{d}\left(t\right) = Ae\left(t\right) - c, \qquad d\left(0\right) = d_0 .$$

where, *c* is the critical load, *r* denotes the interest rate, *C* is the cost function of the reduction of the emissions and *D* the damage function of the depletion of the acid buffer stocks. "*The problem is a game and a game composed of optimal control problems is called a differential game. The static version with flow pollution instead of stock pollution was called the acid rain game (Mähler, 1989; Newbery, 1990). In that tradition the game of this paper is called the acid rain game*". "*Each country chooses a time path for its emissions with the objective to minimize a discounted stream of costs and damages subject to the depletion of the acid buffer stocks*" (page 170).

The authors propose three solution concepts: the open-loop Nash equilibrium (in which the emissions are only function of time, and the game is played as if it were a one-shot game), the feedback Nash equilibrium (in which the emissions are also function of the current state of the system, and the game is dynamic because countries acquire new information during the course of the game) and the full cooperative equilibrium (under side payments).

In the case of full cooperative situation, it is assumed by the authors that all interest rates are equal and the cost and damage functions have simple quadratic functional forms:

$$C_i\left(e_i\right)=\frac{1}{2}\gamma_i\left(e_i-\overline{e}_i\right)^2, \qquad D_i\left(d_i\right)=\frac{1}{2}\delta_i d_i^2, \qquad \gamma_i>0,\ \delta_i>0$$

where, $\overline{e}$ "*must to be chosen high enough in order to ensure that this cost function has a realistic form…, namely decreasing*". The optimal steady-state in this case is given by:

$$e_C = A^{-1}c,$$

"*which implies that the optimal path converges to a situation where the depositions are equal to the critical loads*".

Then, the authors present a computation of the three outcomes in the case of transboundary pollution between England and Ireland and across the whole of Europe. It is demonstrated by the authors that in all of these three cases the depositions converge to critical loads but the speed of convergence and the steady-state depletion levels differ.

The critical load concept has to be accepted to obtain benefits from cooperation. These benefits are higher in the feedback Nash equilibrium, if no side-payments are allowed. If side-payments are allowed, it is possible to reach the full cooperative outcome. What is very important is that the data needed to implement such model are very difficult to obtain and are generally averages, which means that it is very difficult to analyze specific situations.

Another perspective of the problem is given in Okada and Mikami (1992). They introduce the game theoretic setting to assign emissions' reductions of sources in order to reduce depositions at receptors. The model is structured to reduce those emissions affecting specific receptors through acid rain, and the limits are defined accordingly to the maximum deposition for each receptor. Conflicts arise between sources in assigning emissions' reductions to each emission source: "*the more the target level is reduced for one, the less it is for the others*" because the sum of the reductions is fixed. Thus, the problem is to find a fair allocation of burdens of emission reductions.

To represent the idea of the model, we can see the following explicative figures from Okada and Mikami (1992):

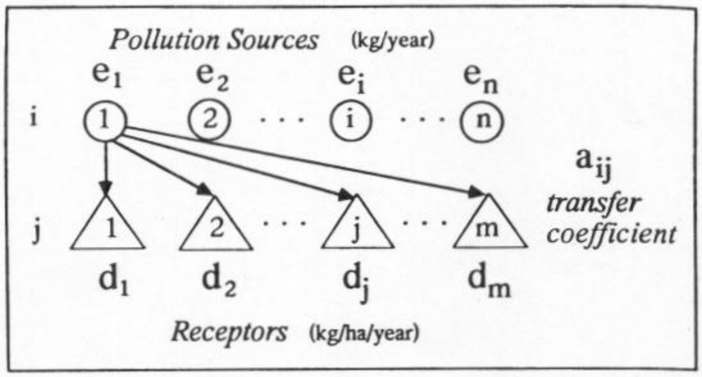

Figure 2. Model Diagram.

Source: Okada and Mikami (1992), page 156

The model follows this procedure:

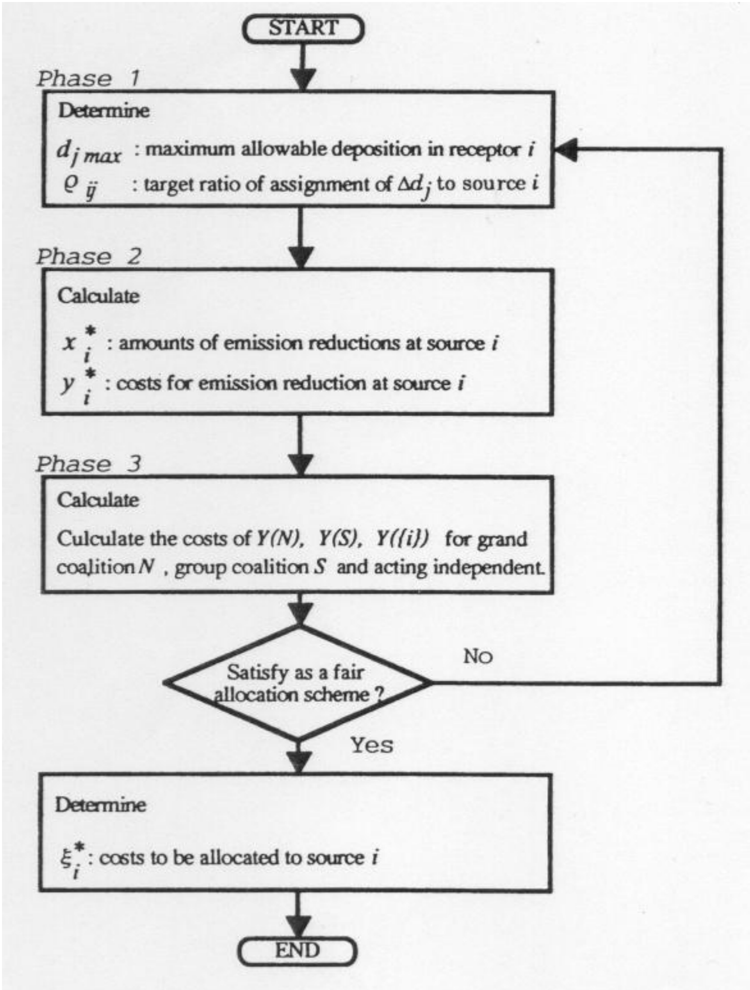

Figure 1. Load Allocation Process

Source: Okada and Mikami (1992), page 156

$\Delta d_j = d_j - d_{j\max}$ is the minimum amount of deposition to be reduced; $d_{j\max}$ is the maximum deposition at receptor j, while d_j is the actual deposition.

Three methods are proposed to determine the target ratio of assignment of this minimum among the emitting sources:

- the first is:

$$\rho_{ij} = \frac{\alpha_{ij}}{\sum_i \alpha_{ij}}, \quad \alpha_{ij} \geq 0;$$

α_{ij} is the transport coefficient representing the ration of the amounts of the loads emitted at source *i* and transported to receptor *j*;

- in the second, the transfer coefficient is weighted by e_i, which is the amounts of emissions at source *i:*

$$\rho_{ij} = \frac{e_i \alpha_{ij}}{\sum_i e_i \alpha_{ij}};$$

- the third mode is called by the authors the *Max-min mode*. It is "*defined as a linear programming problem for each receptor j. The problem is to maximize the lowest bound, ε, on the pollution quotas to average reductions of pollutants per source forming coalition S, such that*

$$\begin{cases} \max \varepsilon \\ \textit{subject to} \sum_{i \in S} \rho_{ij} \Delta d_j \geq |S| \varepsilon \\ \text{for all } (i, j) \\ \text{for any } S(\{i\} \subseteq S \subseteq N) \end{cases}.$$

Given the ratio of assignments, sources must reduce at minimum their costs to reach the targets emissions. Assuming superadditivity, the authors define the way to find the total costs to be shared for the grand coalition *N*, for the intermediate coalitions *S*, and for the single players $\{i\}$ (pay attention that here the characteristic function is the cost function). The problem is formulated as follows:

$$\begin{cases} \min \sum_{i \in N} f_i(x_i) \\ \textit{subject to} \sum_{i \in N} \alpha_{ij} x_i \geq \Delta d_j \quad (j = 1, 2, ..., m) \\ 0 \leq x_i \leq e_i \quad (i \in N) \end{cases}$$

where $f_i(x_i)$ represents the cost of reducing pollutants by the amount of x_i at source i. The first minimization is imposed to guarantee that the emission reductions over all the sources are at least equal to the minimum deposition reduction in receptor j.

Given the optimal solution x_i^* to this optimization problem, we get the optimal total costs:

$$Y(N) = \sum_i f_i(x_i^*),$$

These total costs must be allocated. The authors find the cost for all the *S* sub-coalitions and for the single player coalition. Then, they propose the game theoretic solution concepts to allocate the costs. Two solution concepts are mentioned: the Shapley value and the nucleolus (the references cited by Okada and Mikami are Young et al. (1980) and Suzuki and Muto (1985)). They calculate with real data the ratio of reduction for each of three methods above proposed comparing five different scenarios in term of different α_{ij} for countries; then, they calculate the allocation of costs for both the cooperative solutions and compare the results. In the Shapley value case, "*those sources which have large values for their related transfer coefficients and emissions amounts tend to share the highest costs for any mode(of ratio) assignment*". The same tendency may be observed using the nucleolus.

What is found is that the model can be used as a most effective and equitable alternatives for acid rain abatement.

Forest management

Forest management is an important international issue involving also internal problems, that is, problems between governments and local communities. These problems arise mostly in developing countries, where local communities have different preferences over the uses of the forests.

Kant and Nautiyal (1994) propose a game theoretic approach to solve those issues between governments and local communities. They suppose that a bilateral monopoly is the form of the interaction between those two subjects. This situation occurs because, even if is assumed that property rights are well defined and well known, locally these rights can be un-respected, in absence of monitoring actions, by individuals who draw their sustenance from the forests. They suppose that local communities have the power to negotiate the forests' uses with the government because they can choose their behavior with respect to forests' goods: local communities have their own preferences, over the consumption of forests' goods, which are often different from those of governments.

The only way to guarantee a sustainable management for the forests is to reach cooperation with these local communities: it is guaranteeing the participation of local communities in the decision making process that sustainable cooperation can be reached, because it is important to define rights, duties and the fairness of benefit sharing arrangements as perceived by the two parties that allow to achieve a sustainable agreement. Thus, parties must be equal partners in forest management.

Governments are the owners of the forests, while local communities are the direct users of forests, exploiting timber and non-timber (i.e. fruits, pastures) goods of the forests. The adopted scheme to reach a solution is the Nash bargaining game.

It is assumed that the parties have complete awareness about the consequences of the agreement, about preferences of the other parties, and commit themselves to respect the agreement. Parties are assumed to have equal bargaining strengths. It is assumed that in this game there are no reprisals and if the agreement is not reached, they have to go home with whatever they brought to the bargaining table. W_o and W_c are the fixed (constant during the time) threat points payoffs per hectare per year for the owner and for the community respectively. There are other several assumptions: the decision making is decentralized, the extent of the area, A, to be managed and the rotation length, R, are two negotiable parameters. The discount rate r is assumed to be constant and to be the same for both the parties.

$Q_t = F(R, A)$ are the timber products sold in the market at a constant price P. The return from the forest is constituted also by an annual return due to non-timber products, Q_{nt}.

The share of final timber product at rotation is Z. The authors suppose a single rotation and the fixed threat points are $S_o = W_o RA$ and $S_c = W_c RA$. The present value of the owner's payoff gain is:

$$Y_1 = \frac{(1-Z)PQ_t}{e^{rR}} - \frac{W_o A\left[\mathrm{e}^{rR}-1\right]}{e^{rR}\left[e^r-1\right]},$$

while the payoff for the community is:

$$Y_2 = \frac{ZPQ_t}{e^{rR}} - \frac{(W_c - P_{nt}Q_{nt})A\left[e^{rR}-1\right]}{e^{rR}\left[e^r-1\right]}.$$

The problem is to determine A, R and Z; this problem is solved imposing the first order condition on the equation $Y = Y_1 + Y_2$. Very often it is assumed that not all these parameters are on the bargaining table, because sometimes communities want the area A or the rotation R to be fixed. Thus, the problem is to fix Z and the bargaining process gives the solution to the problem. The authors apply their model to a case study from West Bengal (India).

Other applications

Additional applications of cooperative game theory in several fields are reported in this section. Excluding the application to the biodiversity case, the applications often show the applicability of the cooperative game theory to the issue considered, while they don't give further insights to cooperative game theory.

Pipeline costs allocation

Salant and Watkins (1996) criticized the actual cost allocation rule for the pipeline usage in Canada. This rule is based on the postage-stamp rates principle, in which all the users pay the same amount per unit, or parcel of capacity, independent of transport distances. The authors criticized this approach that is useful only in few cases ("*when there are high fixed connection costs; there is little variation in the distances among the different users' shipments; there are large transaction costs associated with distance-related tolls when users have similar average distances of haul; when system complexity and cost interdependence make cost causation nebulous*" (page 92)), and they introduce several axioms to extrapolate a more fair and reasonable cost sharing rule. They state that there are two basic properties that a cost allocation rule must satisfy:

- the stand alone cost test. This test is satisfied if the cost allocation rule satisfies individual rationality and group rationality, in the common sense of these properties: the cost share borne by each user (group) does not exceed that user's (group's) stand-alone costs;
- the incremental costs test. This test is satisfied the request that no single group of users is subsidizing. This means that the sharing rule must allocate costs to any group at least as large as the incremental costs of including that group on the system.

These two properties are equity or fairness conditions: "*no one should pay costs in excess of its stand-alone costs and no one should pay less than their incremental costs*". An allocation rule that satisfies these two properties, as the authors state, is included in the set of allocations called the Core. But the Core is a set (does not give a unique solution) and this set can be empty. The authors propose a list of other additional fair criteria for a cost allocation rule:

- symmetry: the cost allocation is "*invariant to the labelling of the firms and to the order in which users are added to the system*". They state that this property can conflict with the stand-alone cost test, because in some cases it is through asymmetric cost allocations that one is induced to stay in the system and to contribute to costs in eccess to stand-alone costs;
- decomposition principle: "*no one should have to contribute to portions of the system that they do not use at all*". To apply this concept, the cost of serving any group of users must be decomposable into the costs of the components used by the group;
- monotonicity: "*as total costs increase, allocated costs should also increase, or at least not decrease*";

- consistency: "*the principles used in determining costs shares for the entire set of users should apply equally to subsets of users*".

The authors consider two cost-allocation rules: the nucleolus and the Shapley value. The nucleolus is consistent, symmetric and homogenous. "*The nucleolus has also the property that it maximizes the cost savings of the group of users that has the smallest cost savings among all possible groupings of facility users*". The most important problem of this allocation rule is that it isn't monotonic.

The Shapley value is symmetric, additive (additivity means that if two users or group of users are combined, the cost allocation for these users is the sum of individual user cost allocations) and monotonic with no cross-subsides. They also report that this is an allocation rule that includes the decomposition principle which is expressed by the fact that the Shapley value doesn't charge the players who do not contribute to costs. What is important to recall is that the Shapley value may not be in the Core of a game; on the other hand, it has two important other advantages: it always exist and identifies a unique cost allocation.

The authors also identify which are the main difficulties in implementing these allocation rules. They focus mainly on the Shapley value arguing that "*it is difficult to determine the appropriate manner in which to decompose the cost elements when there is no direct contract between the parties at the receiving node and the delivery node…a system of zonal charges can approximate the ideal cost allocation, and can involve much lower administrative costs*".

They compare the three allocation rules analyzed in the paper in the table reported below, which suggests that the Shapley value results satisfy all the properties.

Table 2: Fairness and Equity Criteria of various solution concepts

	Fairness and Equity Criteria					
	Symmetry	SAC/IC	Decomposable	Determinable	Monotonic	Consistency
Postage Stamp	Y	N	N	Y	Y	N
Nucleolus	Y	Y	N	Y	N	Y
Shapley Value	Y	Y	Y	Y	Y	Y

Notes: SAC/IC = Stand-Alone/Incremental Cost Tests; Y = Yes; N = No.

Source Salant and Watkins (1996), page 101:

Facilities placing

In this subsection we want to report one contribution to the problem of placing useful but not socially accepted facilities, i.e. water treatment plant or incinerator or more in general, as the title of the reference recalls, noxious facilities. The paper we want to cite is Lejano and Davos (2001).

Noxious facilities placing is an important issue in land-use planning. In general, it involves several agents, like towns or communities, which want to build facilities that are environmentally dangerous or not well accepted. To increase the likelihood of acceptance of the facility by society, there can be at least two approaches: the victim compensation and the fair-share criteria (see Lejano and Davos, 2001). In the first case, the acceptance is subordinated to a compensation measure for the less satisfied agents, while in the second the focus in on the subdivision of facilities in a fair way between the agents involved. Both approaches lead towards the resolution of the efficiency–equity dilemma, where efficiency tends toward centralized facilities to take advantage of economies of scale, while equity favors completely dispersed spatial schemes so that the adverse impacts of such facilities are more equitably distributed among participating communities.

The paper adopts the first approach. In fact, it proposes a hypothetical case in which it is shown how cooperative game theory can solve the problem of allocation of disutility between the agents. It is clear that some kind of conflict may arise between the agents in the placing problem, because none of them wants the noxious facility near its jurisdiction. It is assumed by the authors that there exists a "disutility" function that gives the value attributed by each agent to the facility, in term of costs and disutility involved: i.e., a multi-attribute utility function. These functions should be evaluated using some conventional valuation method (i.e., contingent valuation).

The game is a cost saving game in which the aim is to reduce at minimum the costs, expressed in terms of utility function, for the agents.

Two agents must choose the site for the facility between two places, a_1 and a_2. If they play as single player $(n=1)$ in the game, each agent builds its own facility at cost $c(1)$, for player 1 in site a_1, and $c(2)$, for player 2 in site a_2. But they could make a "*cooperative venture*". In this case $n=2$ and players can negotiate the placing of the facility according to their preferences. If the chosen place is closer to player 1, his cost should be higher because his disutility is greater. The opposite holds for player 2. It is necessary to compensate player 1 to accept the facility within its jurisdiction. Methods of compensation allocate to the less satisfied agent an amount that brings him to the so called "Pareto indifference". In this case, the player reaches a position in which she is indifferent between cooperation and non-cooperation. Here the authors propose an allocation of benefits (or cost-savings) that gives to the less satisfied player an amount *greater* than its Pareto indifference point.

Thus, the authors construct a cost saving game and search for imputations satisfying core properties. Within this set, they use the Shapley value and three variants of the nucleolus to demonstrate that it is possible, with the cooperative game solutions, to reach a point that is more accepted by all the players, assuming that side-payments are feasible.

COOPERATIVE SOLUTION FOR THE RESOLUTION OF ENVIRONMENTAL EXTERNALITIES PROBLEMS

This section reviews the evolution of cooperative concepts dealing with international environmental problems. From looking at specific cases, there could be a global dimension characterizing environmental issues and it is reasonable that global welfare could be raised through cooperation among the entire set of interested agents (countries).

However, it is important to recall that cooperation between the entire set of countries involved in an international environmental problem needs that agreements are binding. Since the level is international, there is not a superpower that could guarantee the respect of such agreements. This open the way to the well known free-rider problem, for which several agents could gain in terms of monetary or environmental quality without lavishing any effort.

The issue of free rider opens the way for research on 'self-enforcing' agreements, i.e. agreements that have the feature of being rational and useful for the agents involved and that could guarantee cooperation under any situation. Of course, the way to construct a cooperative agreement depends on the definition of the method of full cooperation between the agents involved, overcoming the coalition formations between few states. This is one fundamental point because there are at least two different school of thought about the ways to guarantee an international optimum (that we will define): the first involves the formation of partial stable coalitions while the second is based on the formation of the grand coalition, including all of the countries interested in the environmental issue (see Tulkens, 1998).

The literature includes economic-ecological models that simulate situations involving several agents that are affected by "multilateral externalities", i.e. "*externalities that each one of the agents involved can both generate and be a recipient of*" (Chander and Tulkens, 1997) These externalities affect countries at different levels: regional, interregional, international, global level, without ignoring the intergenerational level. The most arduous to treat are those at intergenerational level, but we don't treat those in this paper. We are instead interested in those at international level.

Much work has been done in order to find a self-sustaining mechanism, that is, a mechanism that does not need a super-power to survive. Moreover, it is easy to understand how desirable would it be to have cooperation between all of the agents involved in a certain kind of environmental externality. The essence of the problem comes from the heterogeneity of national preferences.

We know (Ioannidis, Papandreou and Sartzetakis, 2000) that this could be considered the fields of International Environmental Agreements (IEAs). For this section we follow Finus (2003), in which are described the most important features of IEAs and the methods to develop them. However, we will consider only those contributes that deal with cooperative game theory, giving details about the models, and following the evolution of the ideas across the time.

Finus (2003) asserts that "*the first attempt to study coalition formation are rooted in cooperative game theory*" and suggest an important reference to study the historical development of coalition theory (see Bloch, 1997).

The most important concept in cooperative game theory is the characteristic function that assigns to each coalition a worth irrespectively to the behavior of the outsiders, since the grand coalition has been formed. "*What irrespective means depends on the assumptions associated with this function*".

Flow pollutants

Following Finus (2003), it is possible to identify at first three papers dealing with the economy with externalities issues, using a negotiation approach giving a payoff structure with a continuous time horizon, sticking to the assumption of a flow pollutant.

Tulkens (1979) introduces an actual case of multilateral externalities. He considers the dumping processes in the North Sea practiced by several European countries. Through these processes each country emits pollutants in the North Sea and is contemporary a recipient of environmental pollution, involving ecological and health damages. The author tries to give an answer to the possibility of having a common mechanism that can optimize the decision making of the countries involved on a voluntary basis (this is an important point, because it addresses the search for the appropriate model); thus, the aim of the paper is to find a process that could contemporary involve emissions reductions and comply with individual rationality, in the sense that each of the countries would be interested..

An economic approach introduces a negotiation process that stimulates all the countries to "cooperate" for a better environment. The negotiation model is structured as a step by step procedure taking into account the following main variables:

1. the willingness to pay of each country for an improvement in the quality of the environment, which is shared by all the involved countries;
2. the costs faced by each country in reducing the discharges relative to the willingness to pay for an improvement of the environmental quality of the whole countries involved;
3. the actual state of the environment;
4. transfer payments between countries to compensate each country's emissions reduction costs, through a share of the surplus from cooperating in the emission reduction and improvement of the environmental quality.

The idea is to develop a negotiation process structured as gradual reductions of discharges over time and implemented through a compensatory transfer payment among countries. The need of a transfer payment between the agents is due to the fact that, along the time path towards the optimum, agents could face situation in which it is not profitable to cooperate.

It creates, indeed, a compensatory mechanism based on the willingness to pay for an improvement in environmental quality and on the costs affecting each country for the emissions reduction (imposed in the negotiation process to be equal to the international willingness to have a better environment), to allow countries to reduce their emissions (which is costly) and a share of the cooperative gains produced by the payments from the countries to improve environmental quality. It is also demonstrated in Tulkens (1979) that the process is individually rational and that goes towards a Pareto optimum.

The model is retaken by several authors. We now formalize it recalling Chander and Tulkens (1992) and Chander and Tulkens (1993). The basis of the paper is the economic-ecological model, verbally mentioned above, in which the pollution is considered as a negative characteristic of the environment; each agent involved has a willingness to pay for its reduction, hence for an improvement of the environmental quality.

In this model, the utility function of a country u_i depends on the consumption of a private good, x_i, and on a single environmental characteristic (the pollution) z; i.e. $u_i = u_i\left(x_i, z\right)$, where $x_i \geq 0$ and $z \leq 0$ (u_i is assumed increasing in both its arguments and $u_i \rightarrow -\infty$ as $x_i \rightarrow 0$ (Chander and Tulkens, 1993)).

The production function $f = \left(y_i, p_i\right)$ depends on the quantity of commodity y_i produced and on the discharges in the environment ($y_i \geq 0$ and $p_i \geq 0$). The ambient pollution *z* is a function of p_i; hence, the externalities are considered multilateral). Thus, x, y and p are considered private goods, while z is considered a public good. For the sake of simplicity, each of these variables is assumed to be one-dimensional, but it is possible that each of these variables is replaced by a vector.

π_i is country *i*'s willingness to pay for an improvement in environmental quality, and γ_i is country *i*'s marginal cost in reducing its pollution:

$$\pi_i = \frac{\partial u_i / \partial z}{\partial z / \partial x_i} = -\frac{dx_i}{dz}\Big|_{u_i = cst} \geq 0 \text{ and } \gamma_i = \frac{\partial f_i / \partial p_i}{\partial f_i / \partial y_i} = \frac{dy_i}{dp_i} \geq 0 .$$

The interaction between the agents occurs in two possible ways: externalities and transfer payments. The presence of transfer payments makes the situation quite different because the commodity used for the production is now written as follows:

$x_i = y_i + T_i$ [12],

[12] In general, we have that $x_i = y_i$ which is the *budget constraint* for the private good consumption, that is the obvious situation in a production process

where T_i are the transfers between countries expressed in terms of consumed commodity ($T_i < 0$ if given away by country i; $T_i > 0$ if received by it).

It is possible to define an "environmental nationalistic equilibrium" (Tulkens, 1979), relative to given environmental behaviors of other agents, as the point in which

$$\pi_i = \gamma_i, \ i = 1,...,n;$$

in the absence of an agreement, each country chooses this strategy in the economy, considering only its own preferences.

The Pareto optimum, instead, is characterized by the following equation:

$$\pi_n \left(\equiv \sum_{j-1}^{n} \pi_j \right) = \gamma_i, \qquad i = 1,...,n.$$

It is important to introduce which are the feasible states of the process, states that are possible for the agents to participate in the economy. They are described as follows:

$$E = \left(x_i,...,x_n, y_1,...y_n, T_1,...,T_n, z \right)$$

such that:

$$x_i = y_i + T_i \qquad i = 1,...,n$$

$$f_i\left(y_i, p_i \right) = 0 \quad i = 1,...,n$$

$$\sum x_i = \sum y_i \quad i = 1,...,n$$

$$z = -\sum p_i \ .$$

It is clear that $\sum T_i = 0$.

The negotiation process is based on the following considerations: the non-cooperative equilibria are characterized as the laissez-faire situation, while the Pareto criterion is taken into account as the the condition for the optimum to be reached. They develop their negotiation process to obtain the stability of cooperation for a flow-type pollution and in a continuous time horizon.

The negotiation process is formulated in terms of gradual changes in z over time, achieved through voluntary reductions in the pollution emission. It requires a complete knowledge of all the utilities, production and transfer function (the transfer function is the function that describes the ecological interactions of the countries involved and that determines z as a function of the pollutant emitted quantity of each country; here it is assumed that $z = -\sum_{i \in N} p_i$: it has the characteristic of a public good, but its effect on all the countries is negative; so the authors refer to is as a public bad).

The process is (these points are given for the first time in Tulkens (1979):

- At every point in time, each country is supposed to provide two numerical values: $\pi_i(t)$ and $\gamma_i(t)$ (this is an important point because what is needed is "local" (time wise) information, not an information that is valid once and for all at the beginning of the process);
- According to the previous point, a change in the discharge for each country is computed:

$$\dot{p}_i = -(\pi_N - \gamma_i);$$

- The sum of such changes then determines the resulting variation in environmental quality:

$$\dot{z} = -\sum_{i \in N} \dot{p}_i ,$$

This sum affects the domestic production of the commodity linked with the discharges, and the production consequently changes:

- The private good consumed and produced are linked with those parameters and are than calculated as follow:

$$\dot{y} = \gamma_i \dot{p}_i ,$$

$$\dot{x}_i = \dot{y}_i + \dot{T}_i ;$$

- The reduction in the domestic production is automatically linked with a transfer payment, which is calculated taking into account both the surplus from cooperation (called "ecological surplus") and an appropriate cost sharing rule:

$$\dot{T}_i = -\gamma_i \dot{p}_i - \pi_i \dot{z} + \delta_i \sum_{j-1}^{n} \left(\pi_N - \gamma_j\right)^2 \text{, with } 0 \le \delta_i \le 1 \text{ and } \sum_{i-1}^{n} \delta_i = 1,$$

where $-\gamma_i \dot{p}_i$ is a compensation payment for country *i* due to its emission reduction costs (or, if $\dot{p}_i$ is positive, the country pays the said amount); $-\pi_i \dot{z}$ is an amount that country *i* pays or receives, according to the sign of $\dot{z}$), proportional to the change $\dot{z}$ in the quality of the environment; $\delta_i \sum_{j-1}^{n} \left(\pi_N - \gamma_j \right)^2$ which is a fraction of the so called 'ecological surplus'.

It is important to note that if transfer payments are null, there are no incentives for the countries to cooperate for any environmental improvement.

As pointed out in Chander and Tulkens (1992), the ecological surplus "*...emerges from the Pareto improving character of the reallocations specified by the process…this surplus being automatically available to the fund as soon as all countries do make and/or receive the payments specified by the first two elements just described*". The authors assumed that there is an agency that collects all the payments and reallocates the surplus. The surplus from cooperation is thus derived from the payments produced by each country for the environmental quality improvement. Thus it is called the ecological surplus $\sum_j \left(\pi_N - \gamma_j \right)^2$.

In describing the sharing rule of the ecological surplus among the countries, there could be room for cooperative game theory considerations.

First of all, we report the proposed costs sharing rule under the ecological surplus:

$$\delta_i(t) = \pi_i(t) / \pi_n(t), \quad i = 1,...,n$$

"*…the consumption cost of the total pollution abatement is borne by each country in a proportion equal to the intensity of its own preferences for environmental quality, π_i, relative to the intensity of the total such preferences, π_n, of the countries involved*".

First in Chander and Tulkens (1992) but most of all in Chander and Tulkens (1993) are given game theoretical justifications to the negotiation process and to the surplus sharing rule proposed above. Here the authors want to explore "*the implication of subsets $S \subset N$ of the countries considering to engage in pollution abatement activities determined by their own preferences only, that is, on the basis of $\pi_S \left(\equiv \sum_{i \in S} \pi_i \right)$ instead of π_n*". At each time, it is considered a local cooperative game $\left[N, v_\delta \left(t, E(t) \right) \right]$ (its characteristic function depends on the time and on the state of the economic-ecological model), where the strategies depend on the reduction of the discharges, the international transfer towards coalition *S* and the international transfer towards the players not in coalition *S*, respectively:

$\left[\left(\dot{p}_i^S \right)_{i \in S}, \left(\dot{T}_i^S \right)_{i \in S}, \left(\dot{T}_j^S \right)_{j \notin S} \right]$, whose elements are defined as

$$\dot{p}_i^S = -\left(\pi_S - \delta_S \gamma_i \right),\ i \in S .$$

The payoff for a single coalition S is:

$$v_\delta \left(S \right) = \sum_i \left(\pi_S - \delta_S \gamma_i \right)^2 \text{, where } \delta_S = \sum\nolimits_{i \in S} \delta_i .$$

The payoff of the surplus form the cooperation among all the countries involved is:

$$v_\delta \left(N \right) = \sum_j \left(\pi_N - \gamma_j \right)^2 .$$

These local games are games with transferable utility in terms of a transferable commodity.

These local games, with the above mentioned sharing rule, have some properties (Chander and Tulkens (1993):

- "*…the strategies of all coalitions $S \subset N$ are such that they all imply for their members: a) the same direction of change in p_i as for the grand coalition N, and b) an at most equal speed of adjustment*";
- "*…the strategy of any coalition never hurts agents that are not members of the coalition*";
- "*…the all players strategy…induces an imputation that belongs to the* ***core*** *of these games.*";
- "*The local cooperative games are convex game…*";
- "*For these local games, the imputation induced by all the player strategy is the Shapley value of such games*"

The authors prove these properties and conclude that they are good arguments in favor of the adoption of the sharing rule, due to the definition of the core of a cooperative game, inducing individual rationality and coalitional rationality for the agents.

These represent the first attempt to introduce cooperative game theory in an economic-ecologic model of the externalities.

Additional analyses proposed by the literature start from the same framework, but are generally structured to make a comparison between the situation occurring in presence and in absence of cooperation, also to understand the behavioral assumption on the players and on the single coalitions that would be formed.

This is introduced in Chander and Tulkens (1995). The basic economic model is quite similar to what is presented earlier, but the willingness to pay and the marginal reduction costs are substituted with the damages and costs functions and the objective is to minimize the sum of these aggregated functions over the entire set of players involved.

In a different model the emitted pollutant is expressed with quantities $E_i \geq 0$, representing the pollutant emitted by agent i per unit of time (even here this quantity could be seen as a vector of emissions of single pollutants); quantities $Q_i \geq 0$ of ambient pollutant present in country i's environment, per unit of time; the transfer function denoting the transformation of the emitted pollutant in ambient pollution, expressed as $Q_i = F_i(E)$, where $E = (E_1, ..., E_n)$ as to say that the environment in each country is affected by the emissions from all the other countries (multilateral externalities). The function is assumed to be of the linear additive form. About this function, we can note that the environmental pollution at each time in each country depends only from the whole emitted pollutant, not even of what could be present in the previous time in the same country's environment. That is, we are treating only flow pollution.

We must also introduce an abatement cost function, $C_i(E_i)$, representing the amount that country i faces to reduce its emissions to the level E_i (this function is assumed to be decreasing), and a damage cost function, $D_i(Q_i)$, expressing the costs of the environmental pollution in each country due to the loss of health and of environmental quality (this function is assumed non-decreasing).

The optimal joint emission would be reached solving the following equation:

$$\min J(E) = \min_{(E_1,...,E_n)} \sum_{i \in N} \left[C_i(E_i) + D_i(Q_i) \right].$$

The solution to these problems is reached by imposing the first order optimality condition on the objective function.

The authors construct a game that can help find a voluntary implementation of the agreement to reach the optimal joint emission, because within cooperative game theory concepts like the core that are useful to reach the optimum and to guarantee the formation of the grand coalition instead of single coalitions.

Here the game is (N, w), with $w(S)$ be the function that associates to each coalition its worth, and can be associated with the economic model imposing that the characteristic function is:

$$w(S)=\min_{(E_i)_{i\in S}}\sum_{i\in S}\left[C_i(E_i)+D_i(Q_i)\right].$$

The solution is reached imposing the first order condition to the objective function:

$$\sum_{j=1}^{n}D_j'\left(E^*\right)+C_i'\left(E_i^*\right)=0, \qquad i=1,...,n,$$

where $E^*=\left(E_1^*,...,E_n^*\right)$ is the optimal strategies' vector that minimizes the costs. It is important to note that the only way to reduce pollution is reducing the emissions, while not considering environmental recovery actions. The Nash equilibrium is reached imposing the first order condition not to the summation, but to the single country's minimization problem.

Having this in mind, let us concentrate on the behavior of the players. At the beginning of the section we have noted that different kinds of characteristic functions occur according to the assumptions relative to the behavior of the outsiders of a certain coalition.

In Chander and Tulkens (1995) it is introduced a particular assumption on the behavior of the players. This assumption is called *partial agreement with respect to a coalition* for which the first order conditions are:

$$\sum_{j\in S}D_j'\left(E^*\right)+C_i'\left(E_i^*\right)=0, \qquad i\in S$$

$$D_j'\left(E^*\right)+C_j'\left(E_j^*\right)=0, \qquad j\in N\setminus S;$$

Thus, they propose that "*when S forms, players outside S do not take particular coalitional actions against S, but adopt only individually best reply strategies. This results in a Nash equilibrium between S and the remaining players, with the players of S playing their joint best response to the individual strategies of the others (it is possible to consider the formation of the entire coalition $N\setminus S$*)" (Chander and Tulkens, 1997).

This is a possible economic situation, which can be translated into a game theoretic concept through an appropriate characteristic function, which is:

$w^{\gamma}(S)=\min_{(E_i)_{i\in S}}\sum_{i\in S}J_i(E)$, where, if $S\neq N$, $E_j=E_j^N \quad \forall j\in N\setminus S$, where E_j^N is the strategy of player j in partial agreement with respect to a coalitional equilibrium. This characteristic function is called by the authors ‘partial agreement characteristic function’, or γ-characteristic function.

In the literature are present other assumption on the characteristic function. The α-characteristic function represents a prudent perception by the members of the coalition S about their capability to guarantee themselves the payoff $v(S)$ if they choose a joint strategy before the joint strategy of the opposition $N \setminus S$ has been chosen, i.e. coalition S can ensure to its members the maximum (total) payoff while choosing its strategy regardless of what the opposition does. This characteristic function follows the max-min approach.

Another common characteristic function is the β-characteristic function, which represents an optimistic perception by the members of the coalition in the sense that the opposition $N \setminus S$ can prevent the players in S from getting more than $v(S)$. Therefore, in the α-framework, a coalition S obtains the payoff it can guarantee itself, irrespective of the strategy choice of the players in $N \setminus S$, whereas in the β-framework, the coalition S obtains the maximum payoff from which it can not be prevented by the players in $N \setminus S$ (Pham Do, K.H., Folmer, H., Norde, H., 2001). This characteristic function follows the min-max approach.

Chander and Tulkens (1995) analyses the α-characteristic function which is defined as follows:

$$w^{\alpha}(S) = \min_{(E_i)_{i \in S}} \sum_{i \in S} J_i(E), \text{ where, if } S \neq N,\ E_j = E_j^{\circ} \quad \forall j \in N \setminus S,$$

where E_j° is the worst strategy that the outsiders can adopt against the coalition S.

For the cooperative solution, we must look for an allocation of the costs which satisfies some properties, taking into account also the behavior of the players.

An allocation $y = (y_1, \dots, y_n)$ is called imputation if it satisfies $\sum_{i \in N} y_i = w(N)$; if it also satisfies $\sum_{i \in S} y_i \leq w(S)$, $\forall S \subseteq N$, the imputation belongs to the core of the game. If transfer payments are allowed, there are more imputations than without transfer payments and those imputations $y^P = (y_1^P, \dots, y_n^P)$ are defined by:

$$y_i^P = J_i(E^*) + P_i, \qquad i = 1, \dots, n,$$

where P_i is the transfer (>0 if the transfer is paid by i; <0 if the transfer is received by i) and it is satisfied the condition $\sum_{i \in N} P_i = 0$. Then, $\sum_{i \in N} y_i^P = w(N)$.

Now to the crucial point. Chander and Tulkens (1995) proposed a theorem to demonstrate that if there transfer payments have the following form:

$$P_i^* = -\left[C_i\left(E_i^*\right) - C_i\left(\bar{E}_i\right)\right] + \frac{D_i'}{D_N'}\left[\sum_{i \in N} C_i\left(E_i^*\right) - \sum_{i \in N} C_i\left(\bar{E}_i\right)\right],$$

and $D_N' = \sum_{i \in N} D_i'$,

then the imputation $y^* = \left(y_1^*, \ldots, y_n^*\right)$ belongs to the core of the game $\left(N, w^\gamma\right)$.

Each individual transfer consists of two parts: a payment to each country i that covers its increase in cost between the Nash equilibrium and the optimum, and a payment by each country i of a proportion D_i' / D_N' of the total of these differences across all countries: each country's contribution is determined by the relative intensity of its preferences for the public good component of the problem.

Taking into account what is proposed in Germain, Toint, and Tulkens (1997) about the transfer payments, it is useful to provide here a brief explanation of the formula that computes the payments that allow to better understand its meaning. Assume that W is the optimal aggregate cost of all countries, W_i the share of W borne by country i (with $W = \sum_{i \in N} W_i$), V_i is the cost for country i in Nash equilibrium and $V = \sum_{i \in N} V_i$ the sum of the total cost of the countries involved in the Nash equilibrium. It is possible, even if the optimal costs are reached in the aggregated situation (W is reached) that are better for the whole community, that some countries do not face a better situation in such an outcome with respect to their Nash equilibrium costs. Then, Chander and Tulkens (1995, 1997) propose financial transfers that are of the following form:

$$P_i^* = -\left[W_i - V_i\right] + \mu_i\left[W - V\right], \quad i \in N,$$

where the parameters μ_i are arbitrary fixed values chosen between 0 and 1 and satisfy $\sum_{i=1}^{n} \mu_i = 1$ (this condition is imposed in order to guarantee that the financial transfers are balanced).

If such financial transfers are considered, the costs for each country are determined as follows:

$\tilde{W}_i = W_i + P_i^*$.

Substituting the transfer payments' formula into the previous equation, we obtain:

$$\tilde{W}_i = V_i + \mu_i \left[W - V\right] \leq V_i, \qquad \forall i \in \{1,...,n\},$$

because μ_i are positive and $W - V \leq 0$ by definition of an optimum.

The solution is considered robust against free riding because "*given the solution proposed to N, the all players set, if some coalition S envisages to free ride by seeking an arrangement of its own, the breaking up of the players not in S into singletons acting rationally is sufficient to make this free riding less attractive to the members of S than the proposed solution*".

The result is subject to the following conditions:

- Damage functions (i.e. preferences) are linear;
- Individual emissions of each country are lower in the social optimum than in the Nash equilibrium;
- Countries are symmetric.

Chander and Tulkens (1997) prove this property in the case of symmetric countries (Finus, 2003).

We can consider other papers dealing with transboundary pollution, assuming a dynamic, though independent payoff function, but considering discrete time intervals and using the γ-core properties. These papers are developed for the acid rain problem and we treat them in one of the next sections (see also Finus, 2003).

Stock pollutants

Germain, Toint, Tulkens (1997) established the transfer payments scheme that was introduced earlier in order to reinforce incentives towards cooperation in the case of stock pollutants, which are pollutants that create environmental damages not only when they are emitted, but also through their environmental accumulations and persistent features.

The model in this paper is formulated in discrete time. The pollutant emissions are $E_t = \left(E_{1t},...,E_{nt}\right)$, expressed as values for each time period t. These emissions are distributed over the entire set of countries and contribute to the formation of the stock pollutant S (≥ 0) which is determined by the equation:

$$S_t = [1-\delta] S_{t-1} + E_t ,$$

where by definition $E_t = \sum_{i=1}^{n} E_{it}$ is the sum of the emissions and δ is the rate of natural decay of the stock $(0<\delta<1)$. Damages are now a function of this stock pollutant, $D_i(S_t)$ (note that countries can control pollution only by controlling their emissions, not with recovery measures), and abatement costs are function of the emission to be reached, $C_i(E_i)$. The assumptions on the damages and costs functions are the same as above reported.

The objective function is now expressed as follows:

$$\min_{\{E_t\}_{t\in T}} \sum_{t=1}^{T} \sum_{i=1}^{n} \beta^t \left[C_i(E_{it}) + D_i(S_t) \right],$$

such that $\begin{cases} S_t = [1-\delta] S_{t-1} + E_t ; S_0 given \\ E_{it} \geq 0, \forall i \in N \end{cases}$

where β is the discount factor $(0<\beta<1)$, $T = \{1,...,\mathrm{T}\}$ and T being the time horizon of the problem (T positive, integer and possibly infinite, even though in the latter case there are other conditions to be made. See Germain, Toint, Tulkens, 1998). The grater the damages and costs, due to real valuation of the damages caused by the pollution, or due to the high discount factor, the lower the emission level in the optimal solution.

Also in this case, the optimal solution is reached by imposing the first order condition on the minimization problem and the solution is a trajectory for the stock towards the optimal emission level.

The assumption here is that the damage function is linear. The authors start with the non-cooperative situation, assumed to be an open-loop Nash equilibrium, and show that properties known for the flow pollutant case extend to the case of stock pollutant. With simple formulas, they show how there can be transfer payments which make the cooperation feasible for all the players, with respect to the Nash equilibrium: the transfer payments, as above reported in the static case, are considered for each time period and it is shown that the outcome for such a transfer payment applied to the cost allocation process gives the same results as in the static case.

Thus, in this paper it is demonstrated that that the γ-core properties are established for linear damage cost function and only for the overall game. The stability is checked as in Chander and Tulkens (1995, 1997), but the players chose their one-shot decision whether to free-ride on the discounted and not on the static payoff (Finus, 2003).

Germain, Toint, Tulkens and de Zeeuw (1998) extend these analyses, introducing a new idea: it is demonstrated that the γ-core properties hold also if we consider that the negotiation over the cooperation takes place not once and for all at the beginning of the game, but it is re-negotiated at each step in time, according to the situation of the pollutant stock.

This result is achieved using the typical ideas of backward induction, showing how, from cooperation at the last (discrete) time period T, it is possible to construct transfers that will allow to cooperate at T-1 as well. And this can be extended for all the time steps in the period.

Multidimensional pollution

So far, we have always assumed that pollution is created by only one kind of pollutant and that the ambient pollution is derived from its transformation in the environment.[13] But we have also said that to consider pollution produced only by a scalar instead of a vector is a restricting assumption. Moreover, there were no considerations of the possibility to have interactions with other pollutants in the environment.

Here we present a paper that relaxes these assumption, utilizing the γ-core framework. This framework extendis the applicability of the core theoretic concepts and was introduced by Chander and Tulkens (1995, 1997).

Figuieres and Verdonck (2003) start introducing the same model of Chander and Tulkens (1995, 1997), which considers a set N of n countries and two kinds of commodities, x and y respectively, consumption and production ones.

They include $m \geq 1$ pollutants (indexed by h), instead of one pollutant, to consider the various possibilities of contaminations of the environment, which are caused by various types of substances. Thus, the emissions are expressed with respect to each country and each pollutant: $p_h^i \geq 0$. The pollution produced by the pollutant h over all the countries involved could be expressed through the vector $\mathrm{p}_h \in R_+^n$ (constituted by non-negative quantities).

Now we are able to rewrite the ambient pollution quantity z_h with:

$$z_h = -\sum_{j=1}^{n} p_h^j , \quad h = 1,...,m .$$

The utility function $u^i\left(x^i, z\right)$ can be expressed as follows:

[13] It should be mentioned that relationship between pollution stock and flow are addressed in economic-ecological models.

$$u^i\left(x^i, z_1, \dots, z_1\right) = x^i + \sum_{h=1}^{m} \pi_h^i z_h , \qquad \pi_h^i \geq 0 , \ \forall i , \ \forall h .$$

Production is assumed to cause some emissions; the authors assume that:

$$y^i = \sum_{h=1}^{m} \log p_h^i .$$

A feasible state of the economy is now a vector $\left(x_1, \dots, x_n, \mathrm{p}_1, \dots, \mathrm{p}_2, z_1, \dots, z_m\right)$, that satisfies $z_h = -\sum_{j=1}^{n} p_h^j$ and the resource constraint is:

$$\sum_{i=1}^{n} x^i = \sum_{i=1}^{n} \sum_{h=1}^{m} \log p_h^i .$$

In such a model, the condition to reach the international optimum is expressed by the following formula:

$$\pi_h^N = \frac{1}{p_h^i} , \ i = 1, \dots, n \ \text{and} \ h = 1, \dots, m ,$$

where $\pi_h^N = \sum_{j=1}^{n} \pi_h^j$.

The authors define the partial agreement with respect to a coalition for such a model and the transfer payments that allow respecting the γ-core properties, showing that it is possible to extend the Chander and Tulkens's formula to this kind of multidimensional models.

CONCLUDING REMARKS

With increased competition over natural resources and environmental amenities, decision makers face strategic decisions in various management and use aspects. Cooperation approaches have been used in many cases, and were proven to be useful under certain conditions. In this review we provide information on various Cooperative Game Theory

(CGT) applications in natural resources such as fisheries, forests, and transboundary acid rain.

Fisheries is the most advanced field to which CGT has been applied, starting from the two-person game to the multi-agent transboundary games and their policy relevance. Given the dynamic and stochastic nature of fishery stock, the problems are much more complicated as they introduce intertemporal considerations. In addition to having CGT applied in stylized cases, several applications to real world cases have been provided: the Arcto-Norwegian cod stock and the North-Atlantic bluefin Tuna.

Due to the nature of the growth curve of fisheries, it is quite possible that, as opposed to other cases, the cooperative bonus of establishing grand coalitions is reduced or disappears due to severe externality problems. This is why in many cases, existing coalitions oppose the entry of new members.

Another common feature of fishery games is that while solution concepts give a unique solution point, in many cases none of them lies in the core, meaning that some players can do better by free riding the grand coalition. The case of RFMO and DWFN suggests that some of the states involved could gain more in a two-member coalition than in the grand coalition; furthermore the coalition which includes the EU has bargaining power and each of its players could be better off without the grand coalition.

APPENDIX I: BIOLOGICAL MODELS OF FISHERIES

Simple model

We introduce the biological model by Schaefer (1954) which is the most used one. The model assumes a single fish stock. The population dynamics are modelled by the equation:

$$\frac{dx}{dt} = F(x) - h(t,x), \quad x(0) = x_0$$

where $h(t,x)$ is the harvest rate (in the case of more than one country h becomes the sum of harvest factors of the countries involved) and $x(t)$ is the population biomass, measured in terms of weight, respectively at time t, while $F(x)$ is the natural growth function. $x(0) = x_0$ is the value of the state variable at the beginning.

In the Schaefer's model:

$$F(x) = rx(1 - x/K),$$

where K is the maximum biomass size and r, a constant, is the intrinsic growth rate (both the intrinsic growth rate and the carrying capacity are determined by the ecosystem), and

$$h(t,x) = qE(t)x,$$

the harvest production function, where $E(t)$ is the rate of fishing effort (the flow of labor and capital services devoted to harvesting fish). Furthermore, it is assumed that $E(t) \in \left[0, E^{\max}\right]$. q, a constant, is the 'catchability' coefficient describing the used equipment capacity to catch a certain fish. The harvest function for the fleet in a country is assumed linear for those countries. Harvest is determined by the catchability coefficient (assumed identical for agents) and the effort employed (total number of vessels/days per unit time or the number of nets, etc). Employed effort is the choice variable for agents exploiting the resource. In these models is also often assumed that both the demand for harvested fish and the supply of fishing are perfectly elastic.

Then the net revenue from the fishery, or resource rent, will be given by:

$$\pi = \left[p - c(x) \right] h = (px - c) E$$

p is the constant price at which fish is sold. Harvester also faces costs ($c(x) = \frac{c}{x}$ is the unit cost of fishing effort) from harvesting which are proportional to the used fishing effort (here the catchability coefficient is assumed $q = 1$). The objective of management from society's point of view is to maximize the present value of the net revenue from the fishery. The resulting optimum in the static case is simply to harvest until marginal revenue is equal to the marginal cost of fishing. The next stage is to analyze the social optimum of harvesting and stock size in a dynamic framework. The approach taken by Clark and Munro (1975) has become the standard model of fisheries economics. In this, the society's maximization problem is:

$$\max J(x_0, E) = \int_0^\infty e^{-rt} \left[px(t) - c \right] E(t)\, dt ,$$

where r is the instantaneous social rate of discount. J is also the so called present value (PV) of the resource.

The solution of this linear optimization problem, subject to the dynamic function of the fishery and with x and h respectively state and control variable, is a unique optimal solution and the optimal steady state resource level x^* is determined by the following equation (Clark [1990]):

$$F'(x^*) + \frac{cF(x^*)}{\left(x^* \left(px^* - c \right) \right)} = r ,$$

in which the instantaneous social rate of discount is equal to the marginal product of the resource, $F'(x)$, and the marginal stock effect, as Clark and Munro (1975) said. In this case the equilibrium solution is unique, and not a function of time.

The optimal biomass level is that level at which the own rate of interest of the resource is equal to the social rate of discount. This solution brings that the optimal approach harvesting path is the most rapid one, such as the optimal effort rate is E^* and:

$$E^*(x) = \begin{cases} E^{\max} & \text{for } x > x^* \\ F(x^*)/x^* & \text{for } x = x^* \\ 0 & \text{for } x < x^* \end{cases}.$$

As mentioned above, x^* is the unique owner optimum defined as the steady state stock level at which the agent reaches his long term optimum. Hence, depending on the initial size of the stock, these strategies regulate resource depletion and recovery.

This is a good management of the resource, which guarantees its recovery and its sustainable exploitation. It represents the management of the resource as there was only one harvester, or there were cooperation between the harvesters.

If the fishery is managed as an open access resource, it becomes competitive and the resource is exploited below x^*. There is no incentive to conserve the resource. In this case,

$$p - c/x^{\infty} = 0.$$

Here x^{∞} denotes the so called bionomic equilibrium (bionomic equilibrium (Gordon, 1954) means that it is a biological and an economic equilibrium). This equilibrium represents the value at which agent's economic revenue from the fishery becomes zero, i.e.:

$$x^{\infty} = c/p.$$

We have that $x^* = x^{\infty}$ if and only if $r = \infty$. Since the social rate of discount is often less then infinity, $x^{\infty} < x^*$ and the resource is overexploited.

To complete this introduction of the bio-economic model of fisheries, we can introduce the strategies occurring when there is a non-cooperative behavior of two harvesters. In such a case, it is assumed that the players' behavior follows the Nash non-cooperative feedback equilibrium.

When there are two harvesters, it is generally true that one is more efficient then the other. Assuming that 1 denotes Country 1 and 2 denotes Country 2, we suppose that $c_1 < c_2$, hence that $x_1^{\infty} < x_2^{\infty}$: Country 1 is more efficient and the bionomic equilibrium reached by this Country is lower (we can think it as the less conservationist harvester). In this case the harvest non-cooperatively assuming a certain stock level at time t when they begin to exploit the resource. Their strategies will be as follow:

$$E_1^N(x) = \begin{cases} E_1^{\max} & \text{for } x > \min\{x_1^*, x_2^\infty\} \\ F(x^*)/x & \text{for } x = \min\{x_1^*, x_2^\infty\} \\ 0 & \text{for } x < \min\{x_1^*, x_2^\infty\} \end{cases},$$

$$E_2^N(x) = \begin{cases} E_2^{\max} & \text{for } x > x_2^\infty \\ 0 & \text{for } x \leq x_2^\infty \end{cases}.$$

Depending on the initial stock size and on the relative amount of x_1^* and x_2^∞, we have different situation in the exploitation of the resource. The more relevant situation, that makes us sure that some kind of cooperation is needed, is the following: assumes that $x_0 > x_2^\infty$. In such a case, Country 2 does not take part in the utilization of the resource. Thus, Country 1 will choose its strategy to eliminate Country 2 from the exploitation and the resource is utilized at a maximum capacity until the less efficient Country is obliged to leave the fishery. But in such a case, it is not possible for Country 1 to reach the optimal management level x_1^*, since if it allows that $x(t) > x_2^\infty$ agent 2 will enter the fishery.

It is clear that some kind of cooperation is needed, both as regard the resource and as regard the net revenues for the harvesters.

Multi-variable model

There are several more complicated, but realistic, kind of models describing fish's stock growth. One type of these are the cohort models. Here, the population at a certain time is divided into subclasses, according to the age of the fishes. Instead of a single state variable, the biomass x at time t, the state variable is a vector $x = (x_0, x_1, ..., x_k)$ where k is the age of the fish which, at each time t, describes the situation of the stock.

Such a population structure brings more complications and needs a greater number of specific variables. In fact, it is necessary to know the catchability coefficients (due to the selectivity of the fishing endowments) relatively to the age of the fish or the parental interactions that affect the recruitment of the specie. It is clear that in such a model the data availability should be greater then in the previous one, and this is the main reason for which they are not much used.

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